

# The Origin, Age, and Stratigraphy of Mars' South Polar Cap

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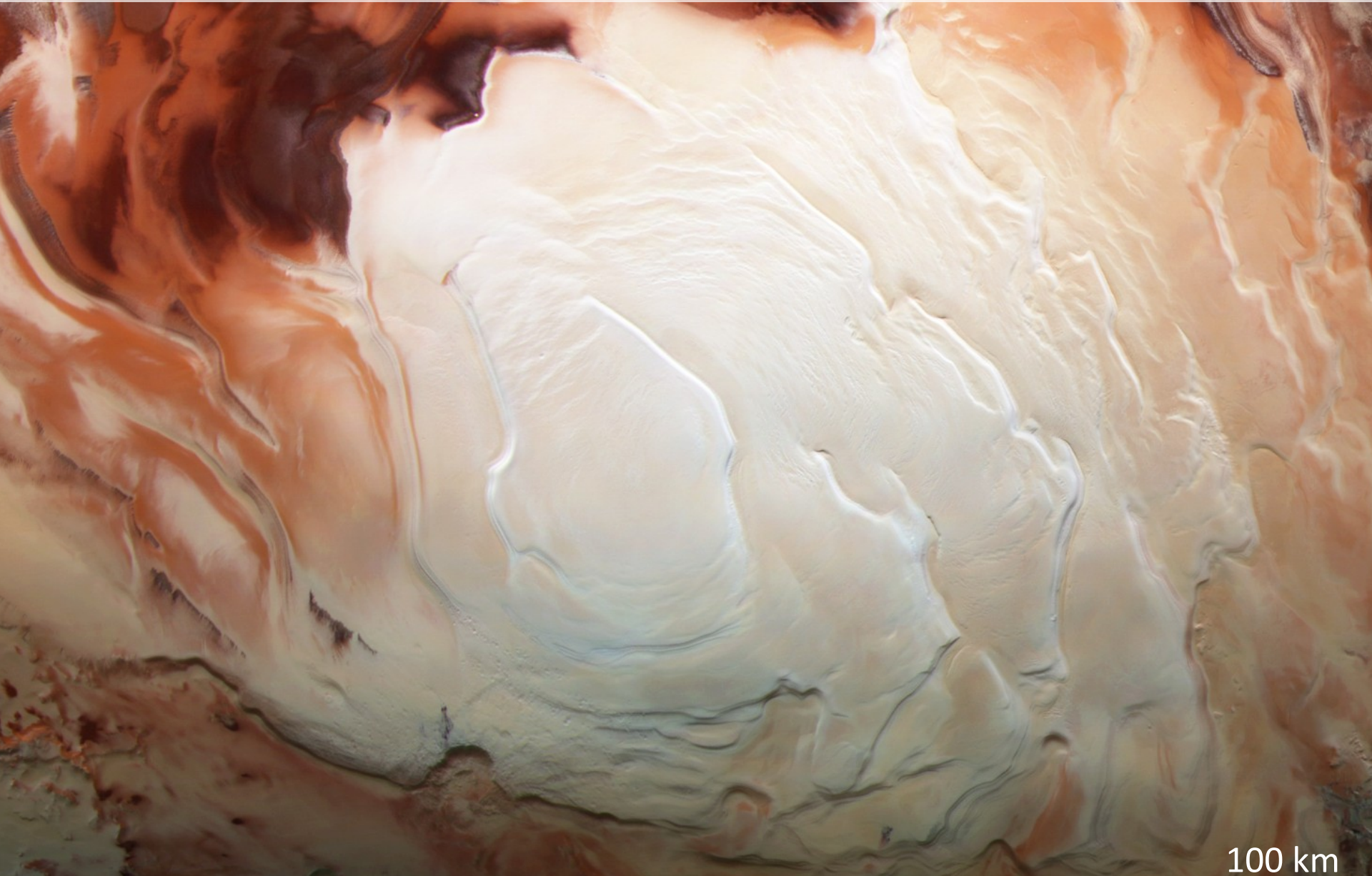
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Caltech Planetary Science Seminar

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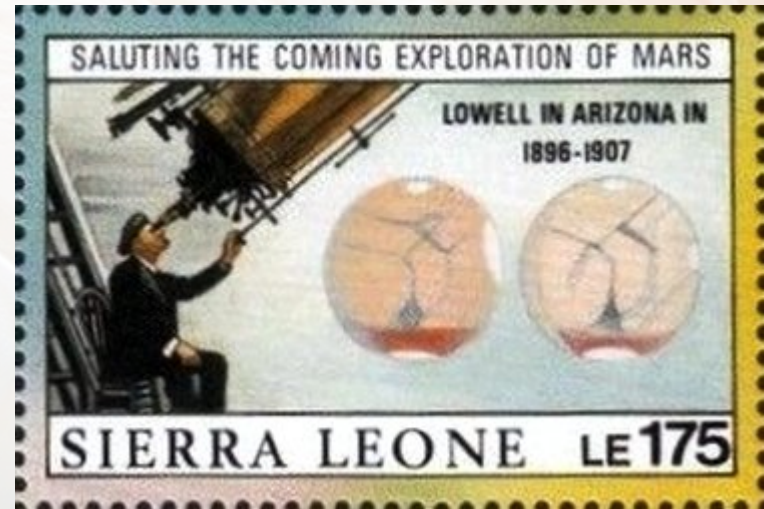
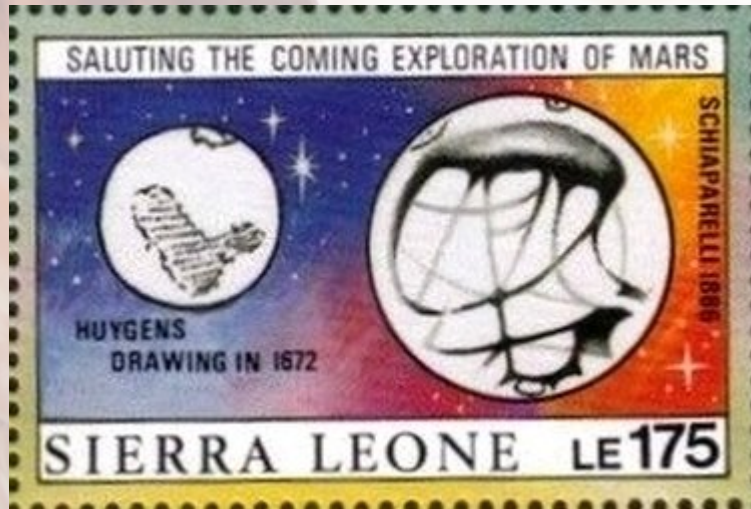
# Mars' South Polar Residual Cap



100 km



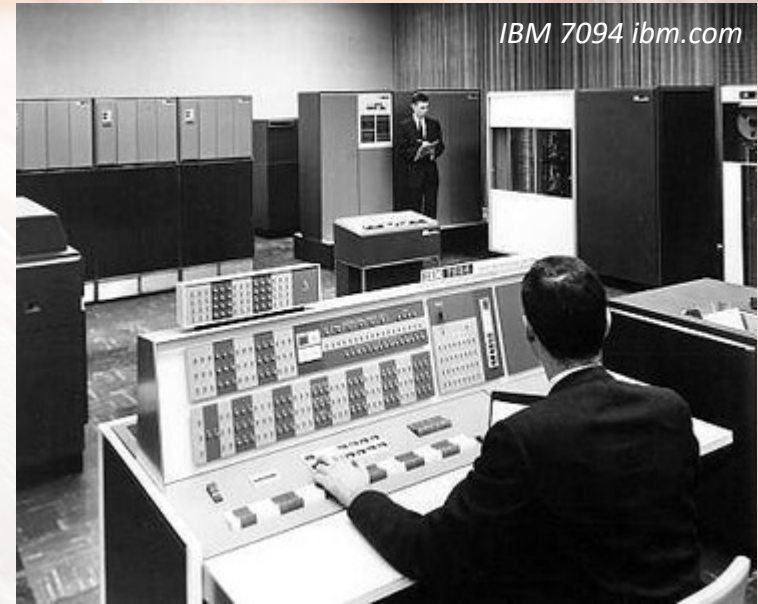
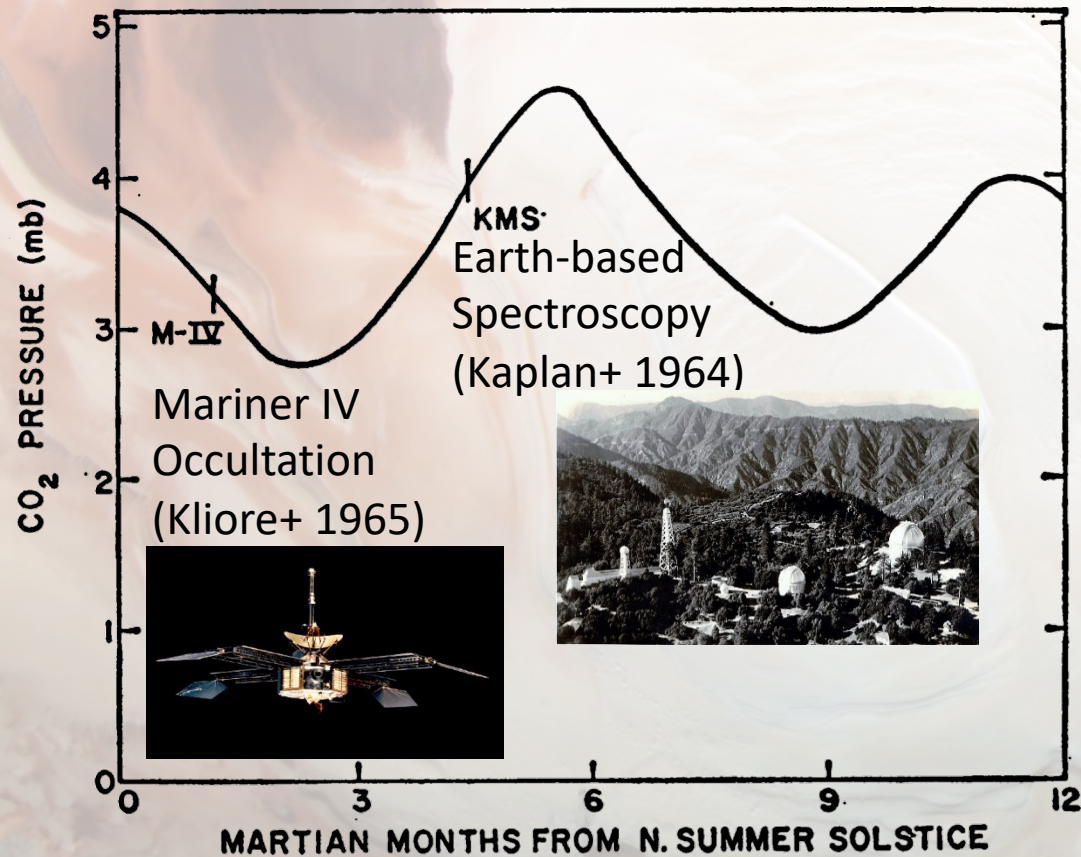
# The Beginning of Mars Polar Observation



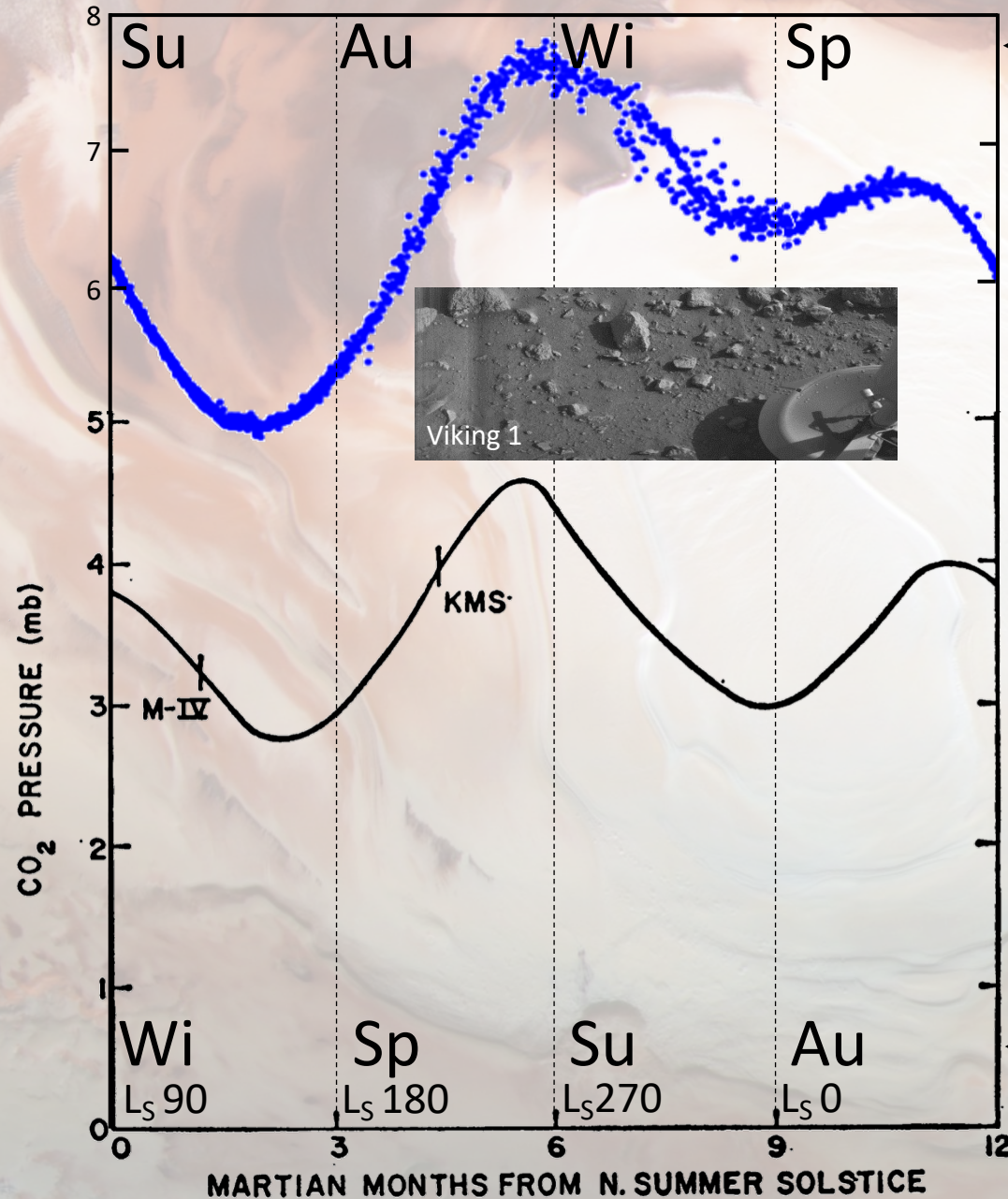
# Air Force Map of Mars (1960)



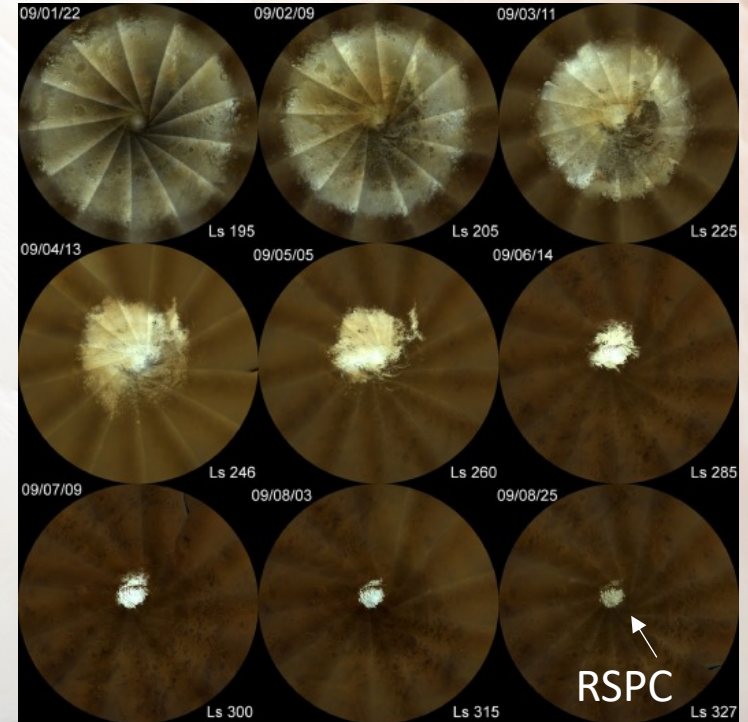
# Leighton and Murray (1966)



# Mars' Seasonal CO<sub>2</sub> Cycle



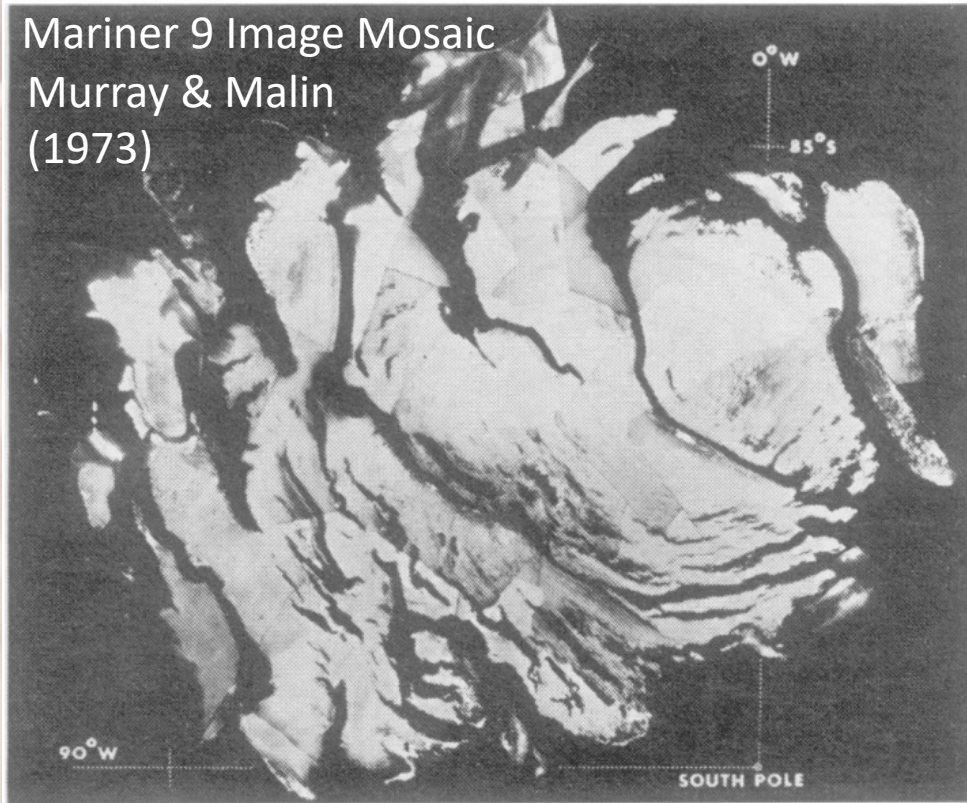
## South Polar Seasonal CO<sub>2</sub>



*Calvin+ (2015)*

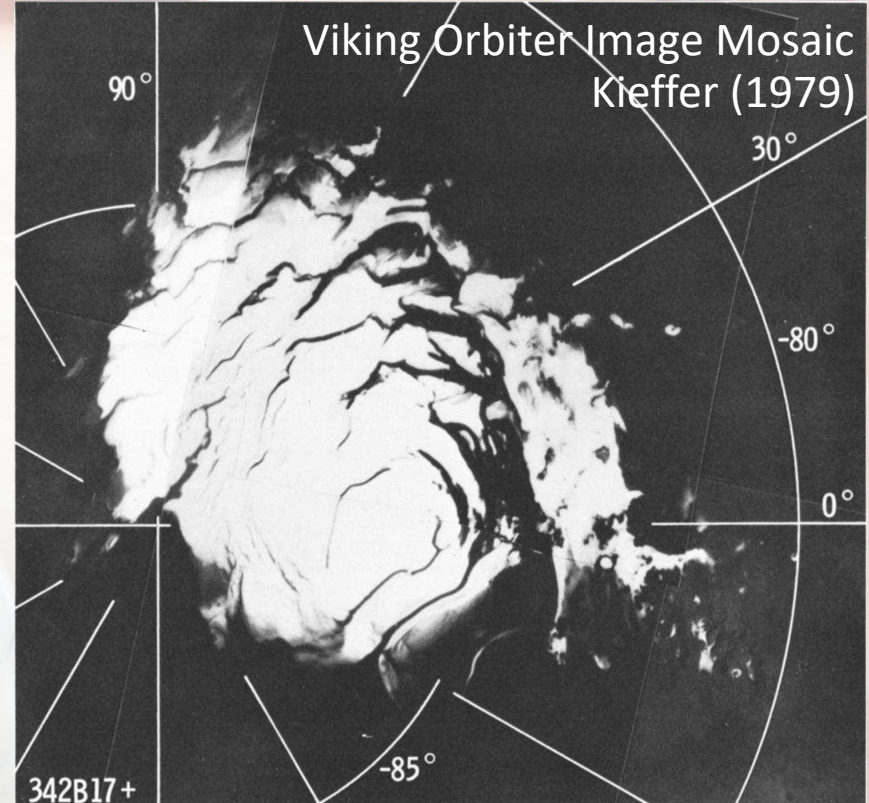
# What is the RSPC?

Mariner 9 Image Mosaic  
Murray & Malin  
(1973)



- “CO<sub>2</sub> ice could not survive in contact with low-albedo material.”
- “Therefore, a residual water-ice cap is much more stable than a solid CO<sub>2</sub> one on Mars in the summertime.”

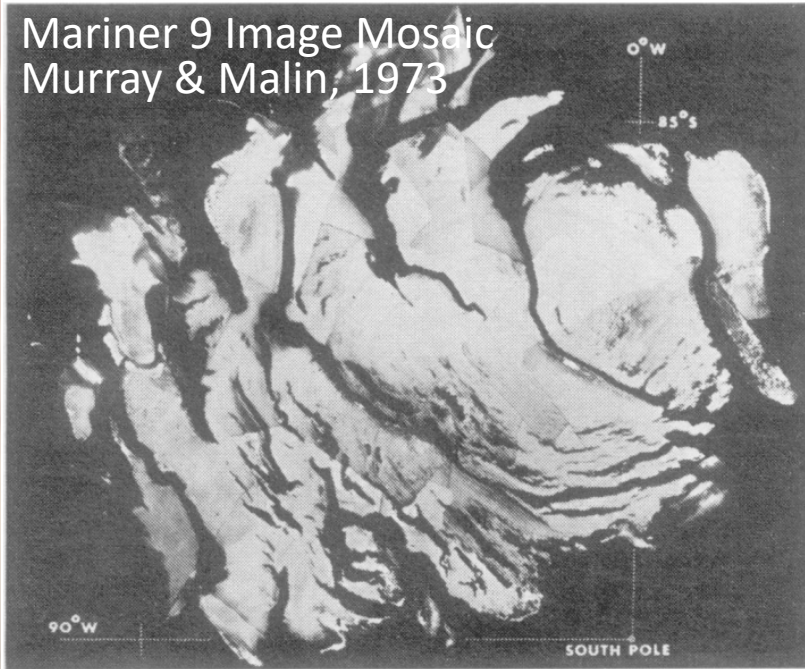
Viking Orbiter Image Mosaic  
Kieffer (1979)



- “Throughout the summer, the polar frost remained at the temperature of solid CO<sub>2</sub>.”
- “Thus Mars appears to have a residual polar cap of CO<sub>2</sub> in the south and one of H<sub>2</sub>O in the north.”

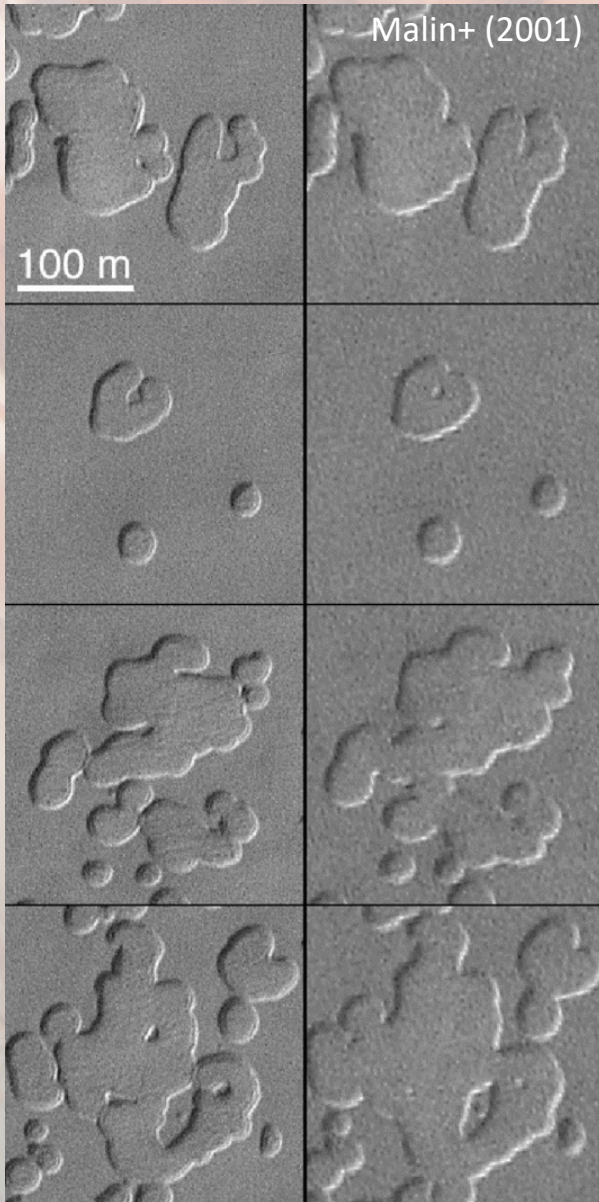
# OK, it's CO<sub>2</sub>, but why at the South Pole?

Mariner 9 Image Mosaic  
Murray & Malin, 1973



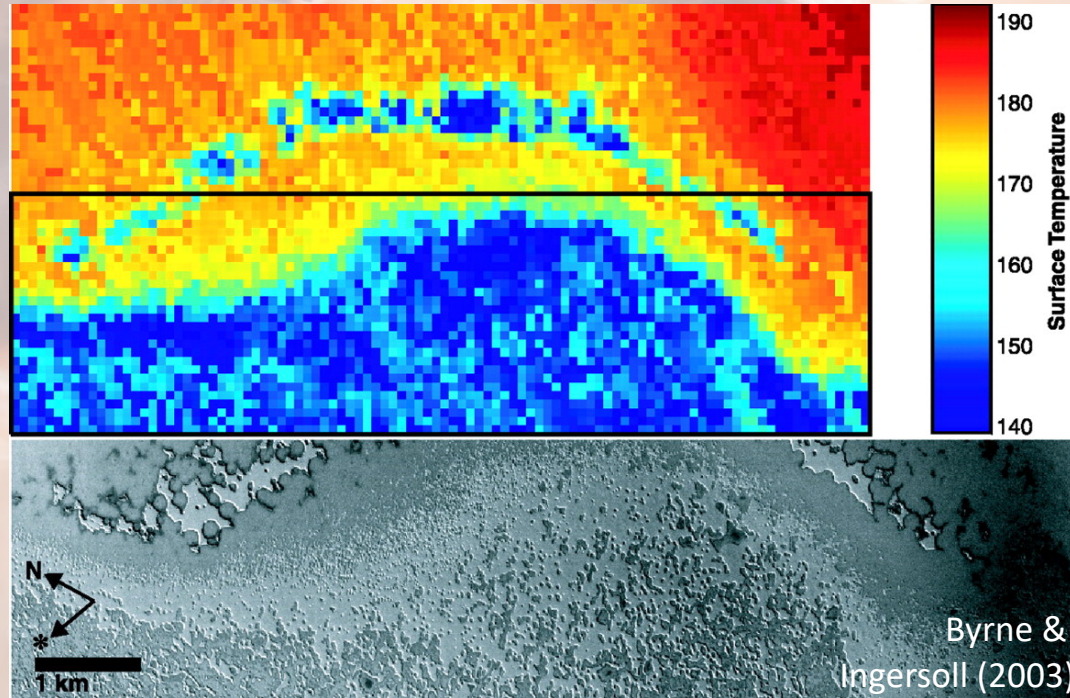
- “[From occultation] it can be seen that the southern residual cap must be higher than the northern one by at least 2 km.”
- “Any solid CO<sub>2</sub> in the south would be in contact with atmospheric CO<sub>2</sub> at a pressure lower by about 2 mbar than in the north.”
- “There is no reason to suppose a permanent CO<sub>2</sub> southern cap would be at a systematically lower temperature than the northern one.”
- “Hence, solid CO<sub>2</sub> deposits in the south would be out of equilibrium and would gradually be transferred to the north...in well under 1000 years.”
- “Excess solid carbon dioxide is probably present [buried] in the north residual cap.”

# And maybe it's disappearing?



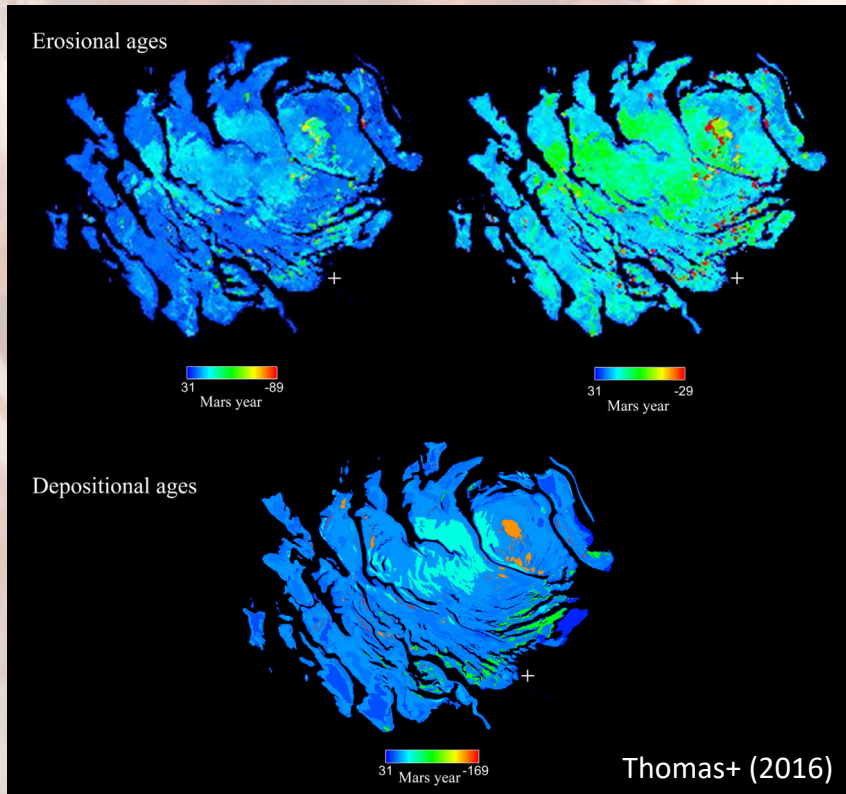
- “The erosion implies that this reservoir is not in equilibrium with the present environment and that global climate change is occurring on Mars.”
- “These and other observations suggest that the present martian environment is neither stable nor typical of the past.”

# And maybe it's disappearing?

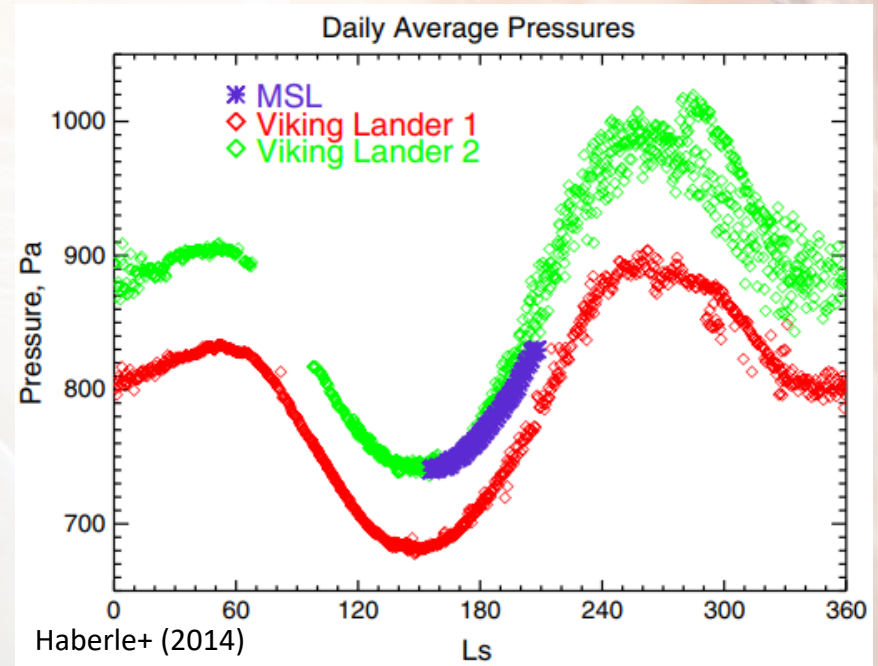


- “The implication is that both polar caps are predominantly composed of H<sub>2</sub>O ice, although a veneer of CO<sub>2</sub> ice covers the south cap.”
- “The upper 8-m layer will be removed in a few martian centuries, [but likely] has some rejuvenation mechanism.”

# Or maybe not?

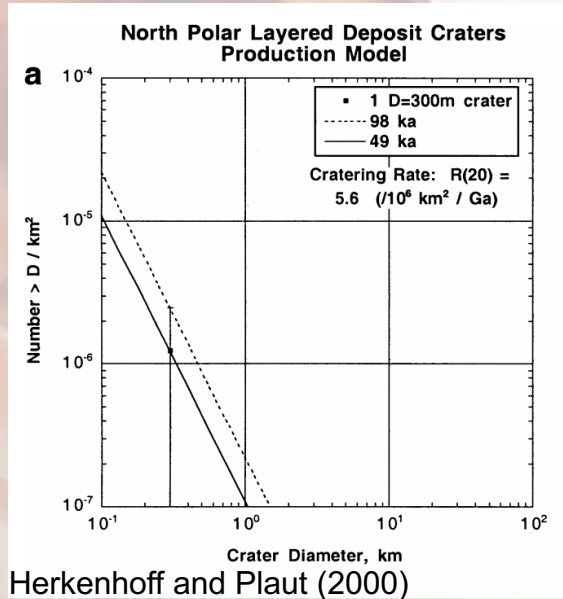


“We find the mass balance in Mars years 9–31 to be  $-6$  to  $+4$   $\text{km}^3$  per martian year, or roughly  $-0.039\%$  to  $+0.026\%$  of the mean atmospheric  $\text{CO}_2$  mass per martian year. The indeterminate sign results chiefly from uncertainty in the amounts of deposition or erosion on the upper surfaces of deposits (as opposed to scarp retreat).”

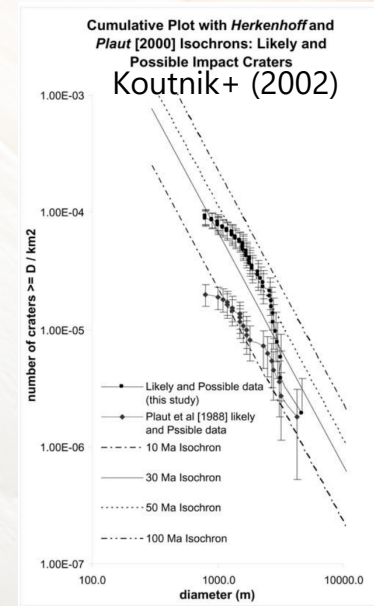


“When compared to Viking Lander 2 data, the REMS daily average pressures show no evidence yet for the  $1$ – $20$  Pa increase expected from the possible loss of  $\text{CO}_2$  from the south polar residual cap.”

# Also, why is the South Polar Layered Deposit (PLD) much older than North PLD?



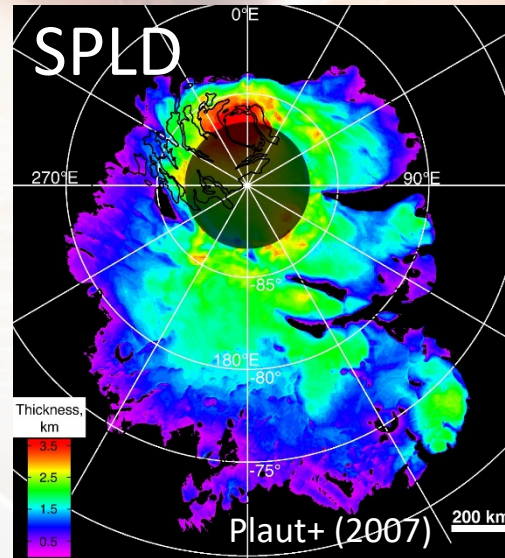
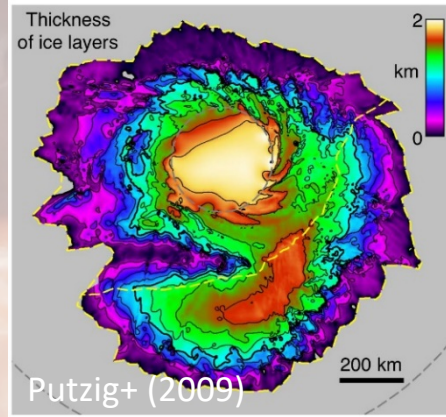
- “[From crater counts], the inferred surface age of the south polar layered deposits (about 10 Ma) is two orders of magnitude greater than the surface age of the north polar layered deposits and residual cap (at most 100 ka).”



- “From these new statistics, we estimate the mean apparent surface age of the SPLD to be 30–100 Ma, depending on the established production model isochrons used.”

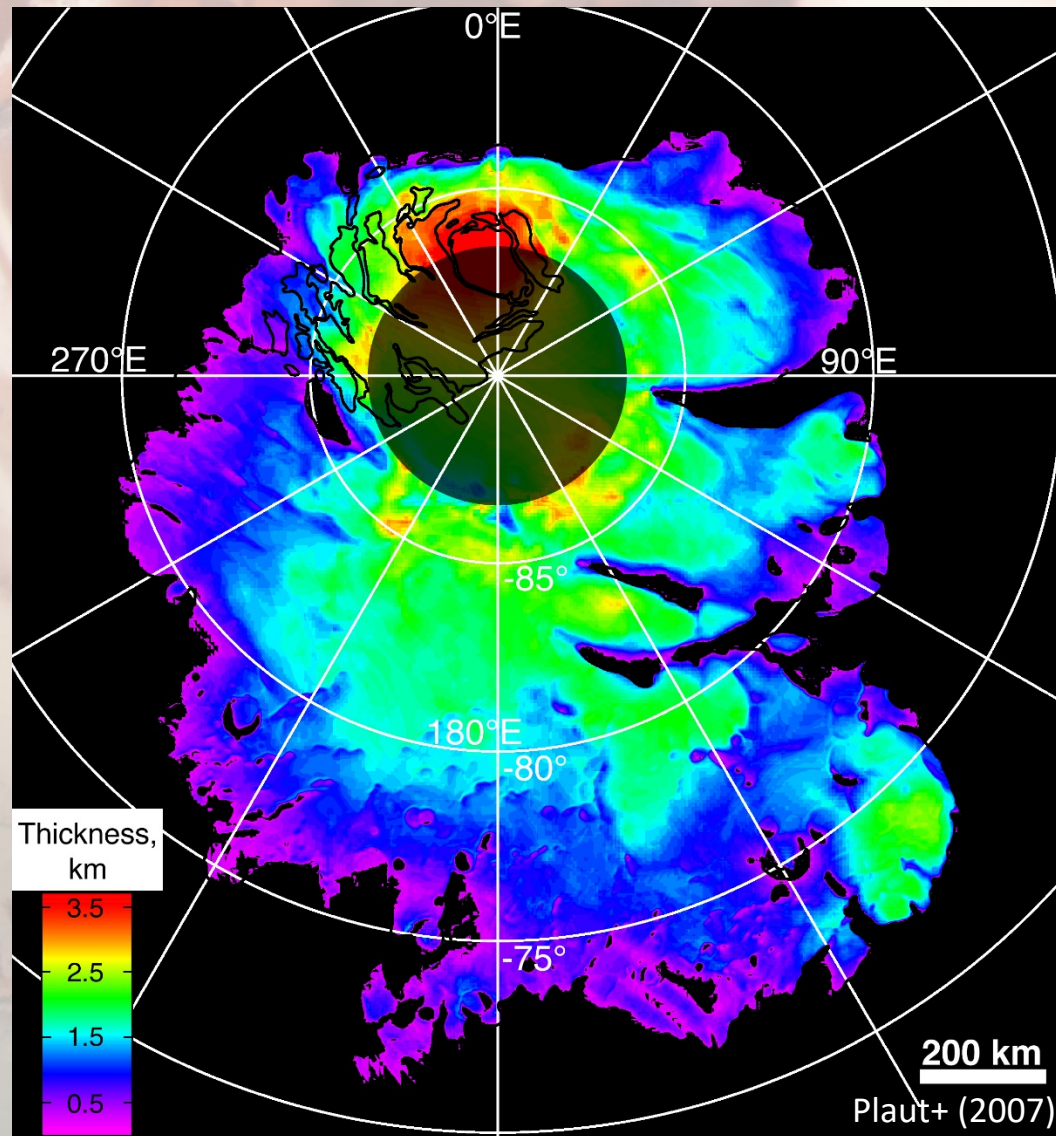
# And older than model predictions?

NPLD



- “Over the last 4 Myr, most of the present [northern] cap may have formed at the expense of tropical and high-latitude reservoirs.” – Levrard+ (2007)
- “The average difference in sublimation will result in net south-to-north transport of water ice over long timescales. As a result, the south cap should shrink and the north cap expand in areal extent.” – Jakosky+ (1993)

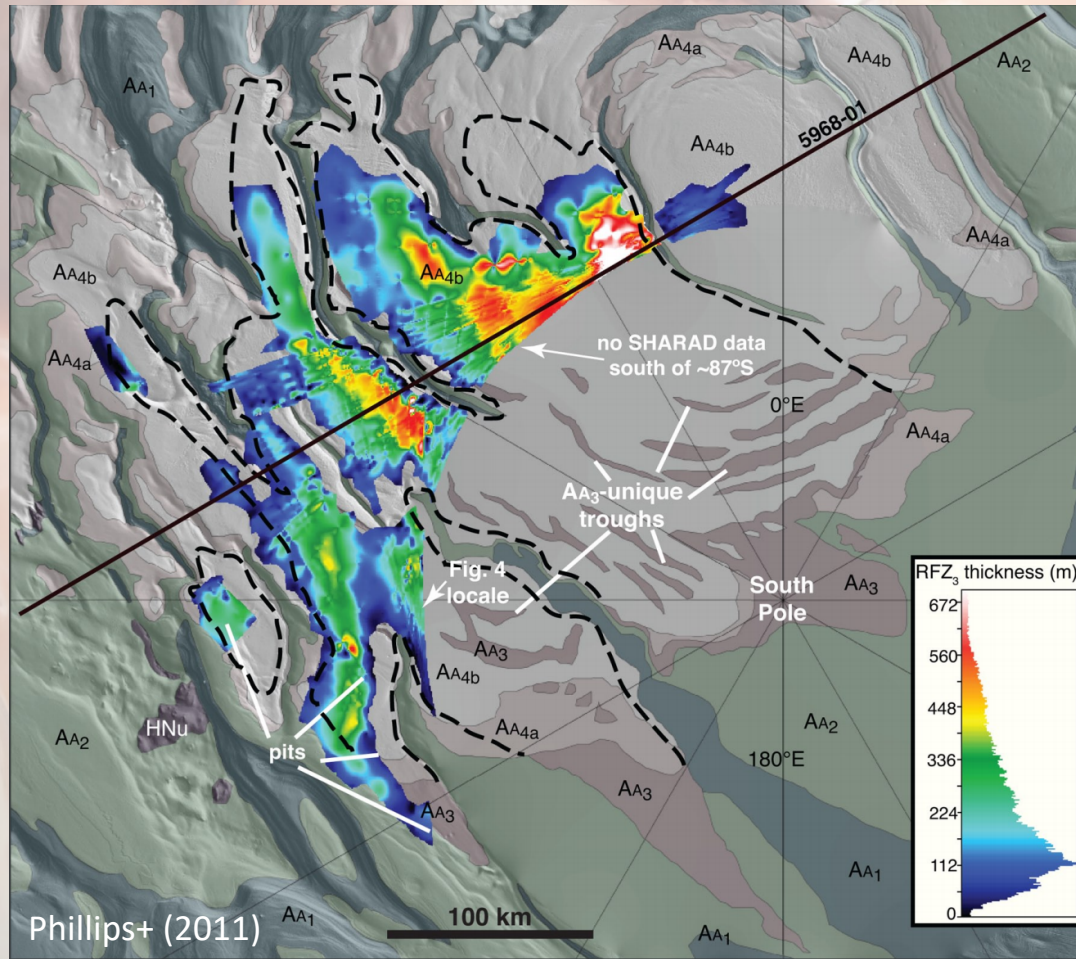
# Radar: south polar cap mostly H<sub>2</sub>O



“It would have to be considered an extraordinary accident if the total CO<sub>2</sub> released over the history of Mars and now available at the surface should just exactly equal that required for the formation of the observed annual caps: a small proportion less and hardly any annual caps would form at all; any larger amount would be in the form of buried solid.”

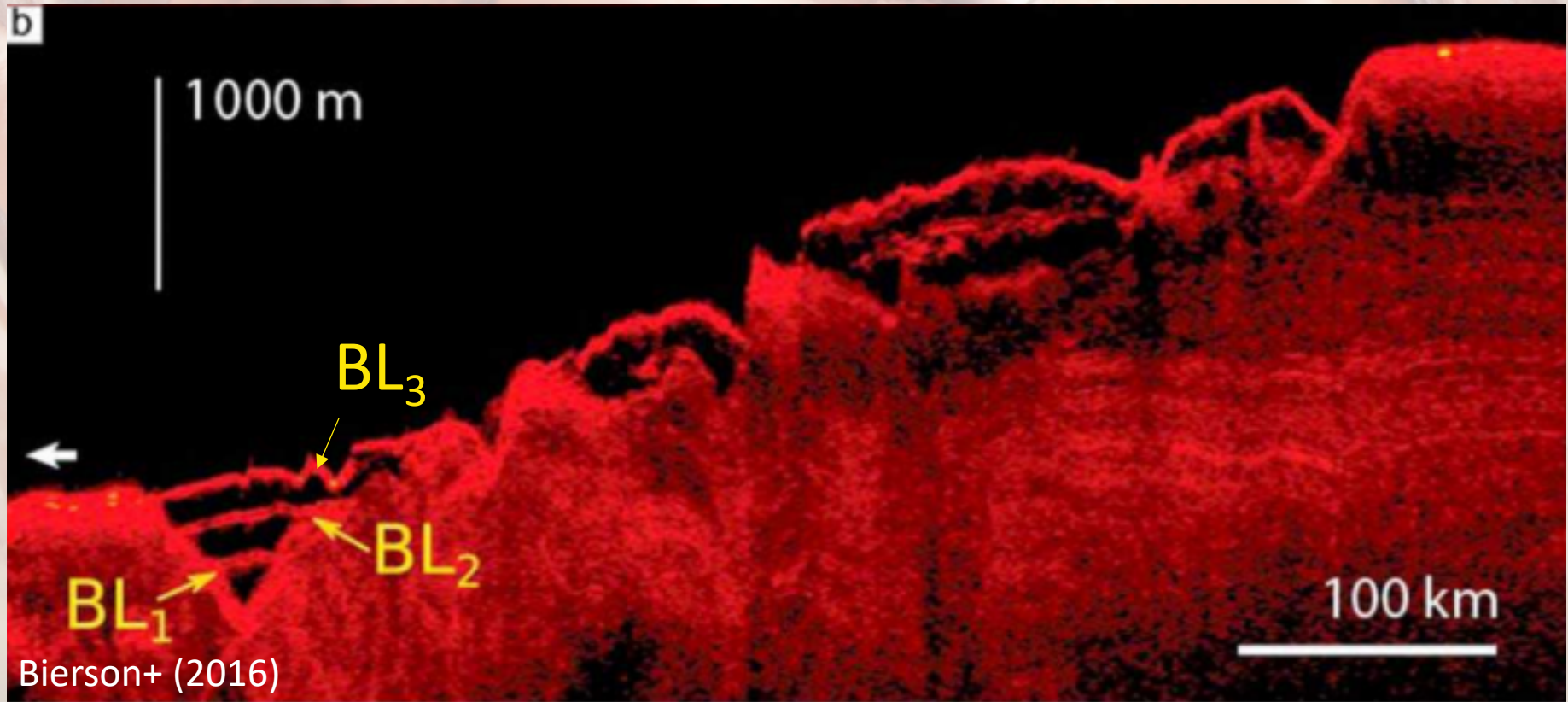
—Murray and Malin (1973)

# But there is a massive (south) CO<sub>2</sub> deposit!



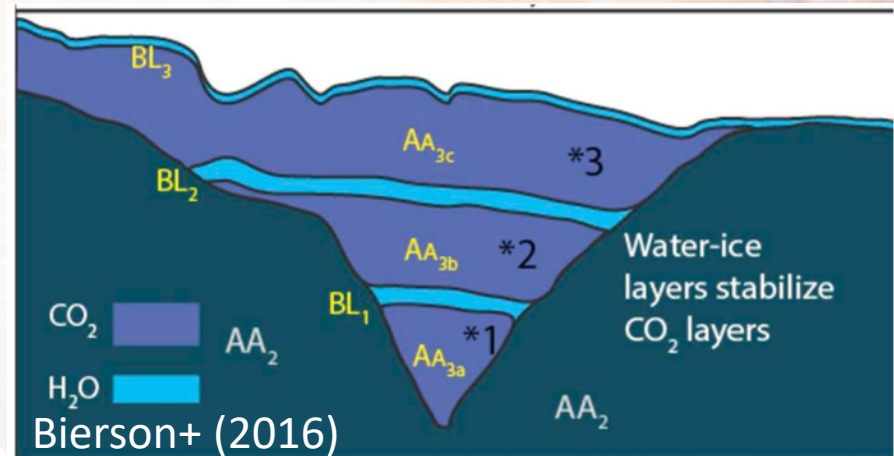
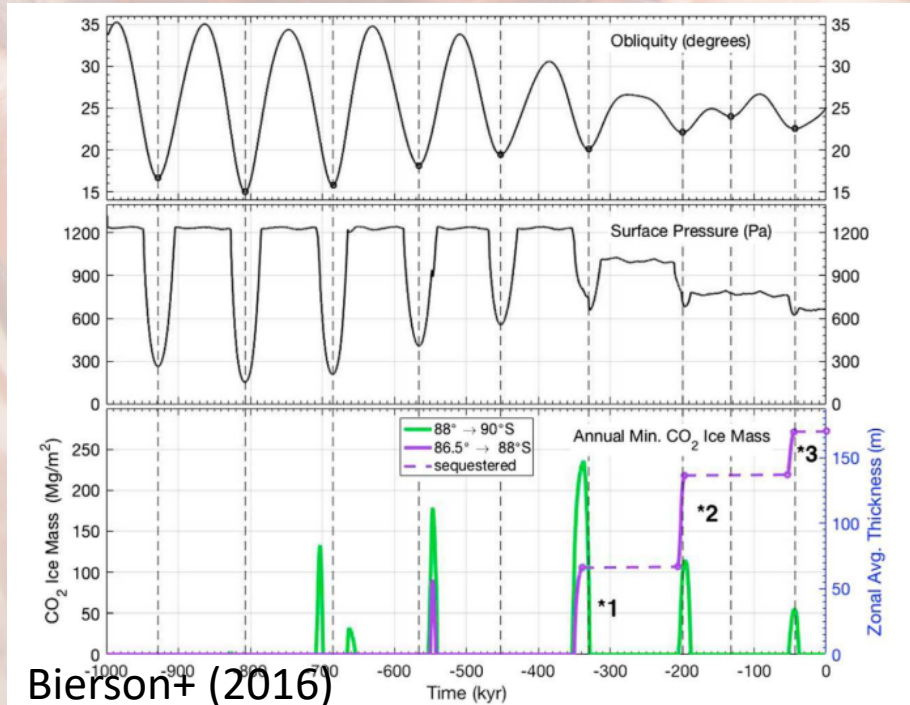
“If released into the atmosphere at times of high obliquity, the CO<sub>2</sub> reservoir would increase the atmospheric mass by up to 80%.”

# The massive CO<sub>2</sub> deposit has layers



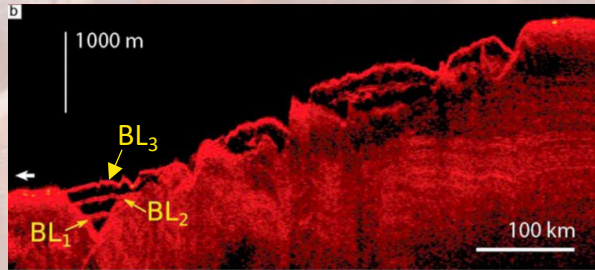
“We find three distinct CO<sub>2</sub> subunits, each capped by a bounding layer (BL).”

# How was it emplaced?



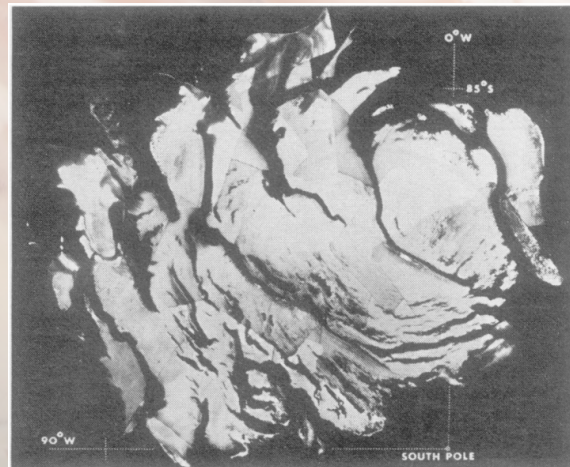
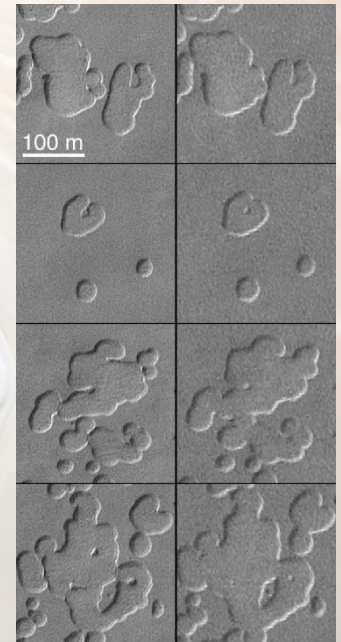
- “CO<sub>2</sub> ice is deposited over much of the poles during low obliquity periods.”
- “A remnant is sequestered below a water ice deposit (BL subunits), removing it from contact with the atmosphere.”
- “Our base model does not sequester the [CO<sub>2</sub>] ice, and it returns to the atmosphere at the end of each period of high obliquity.”
- “However, the presence of the [massive CO<sub>2</sub>] unit requires some mechanism to stabilize and protect the deposit in periods of high obliquity.”

# 4 Outstanding Questions

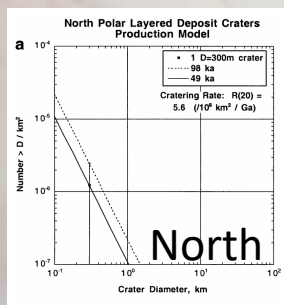


1. How was the massive CO<sub>2</sub> deposit emplaced with its observed stratigraphy?

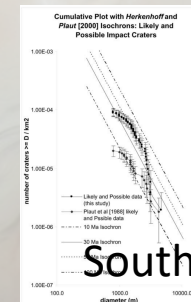
2. Why does the RSPC exist?



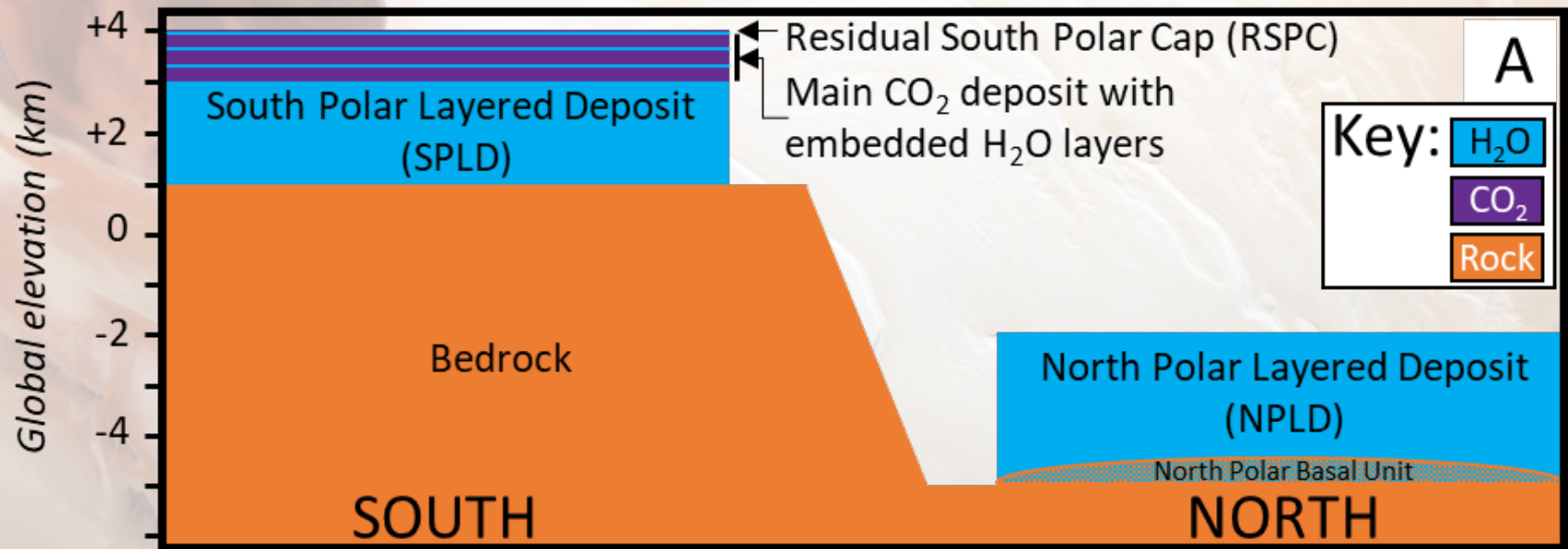
3. Why is permanent CO<sub>2</sub> at the south pole (not the north)?



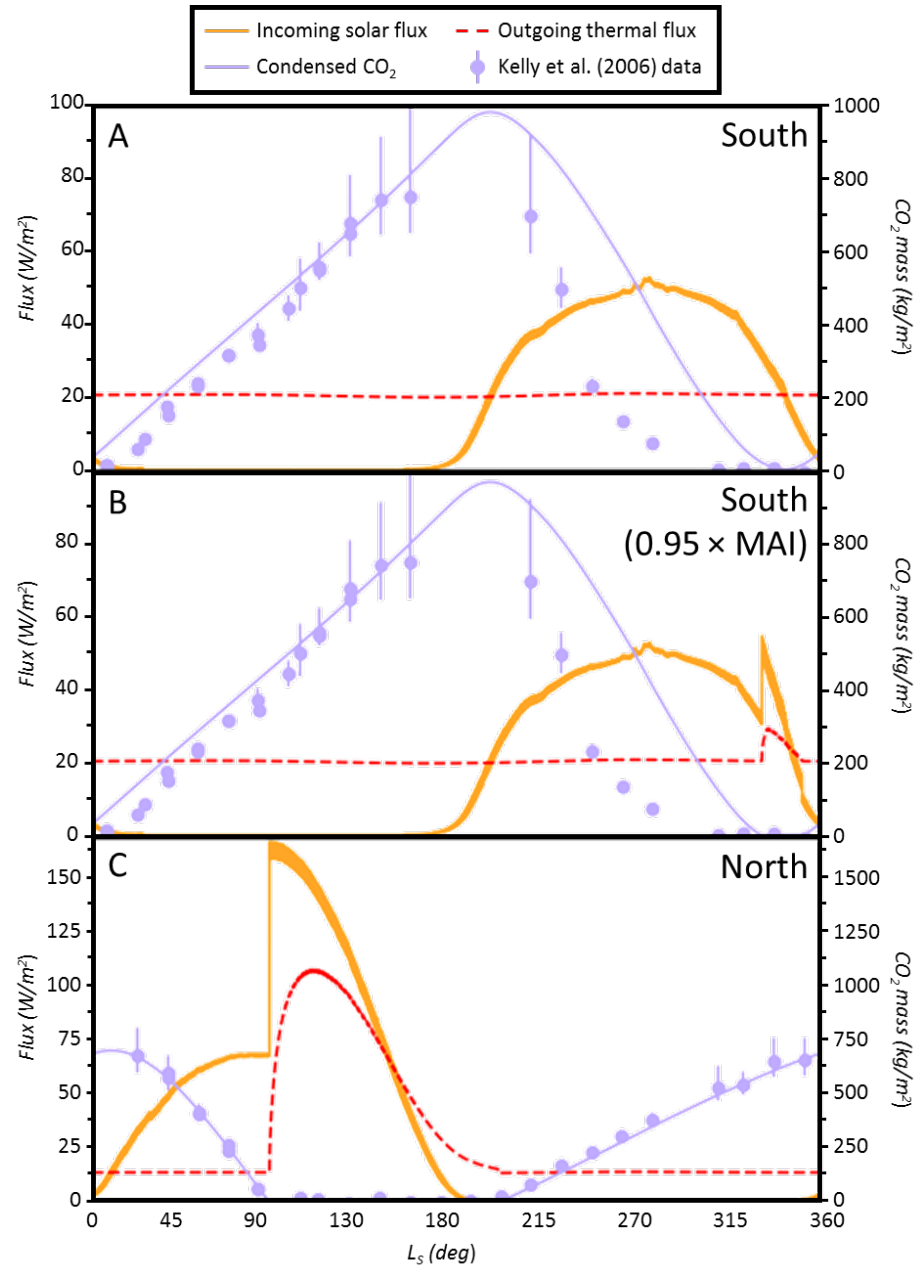
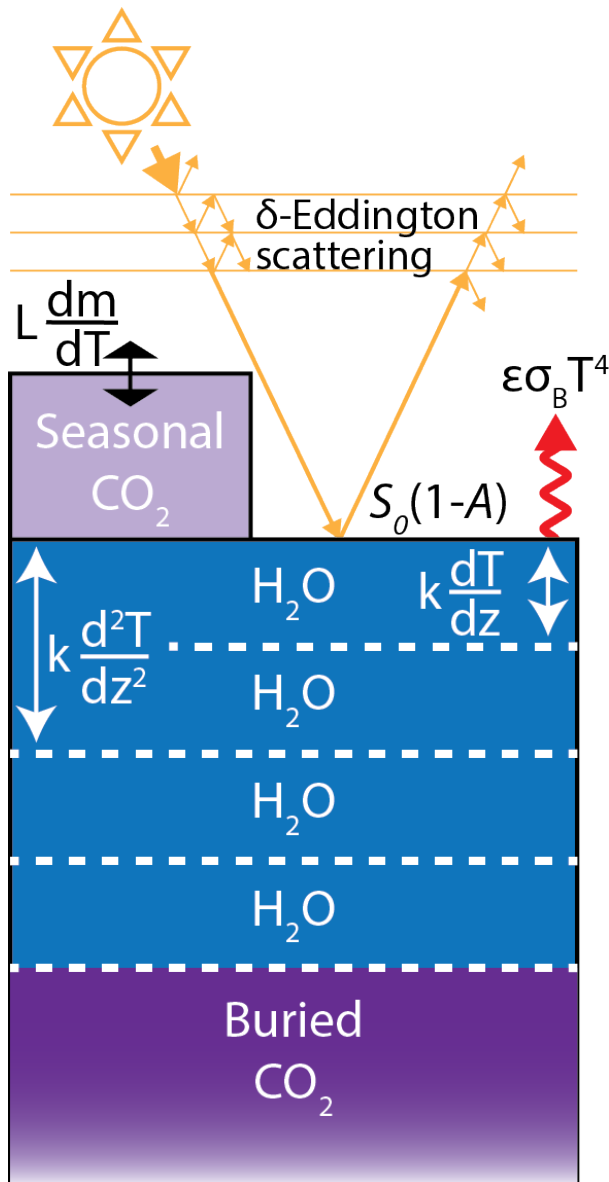
4. Why is the SPLD so old (compared to the NPLD and model predictions)?



# Schematic Polar Stratigraphy



# Energy Balance Model Description



# Is the RSPC an extraordinary accident?

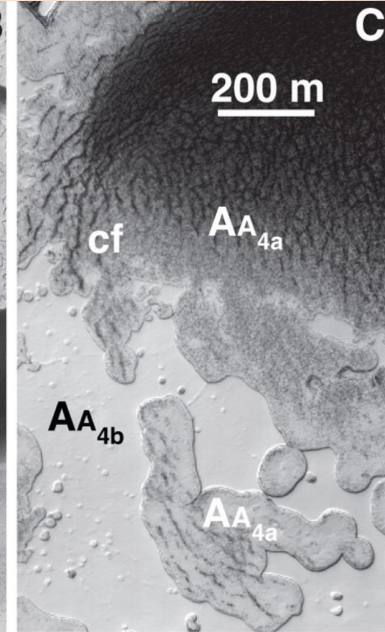
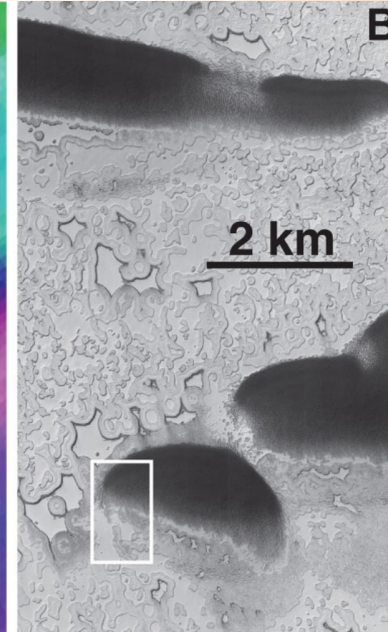
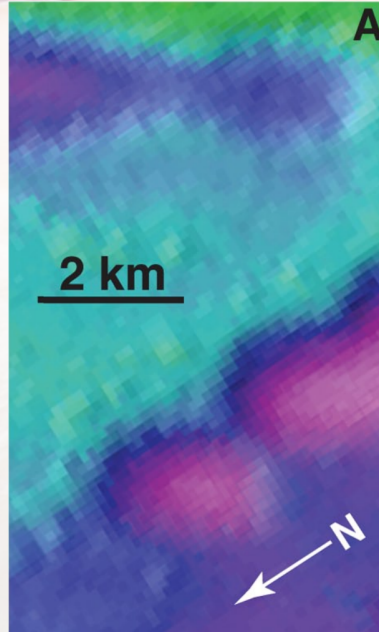
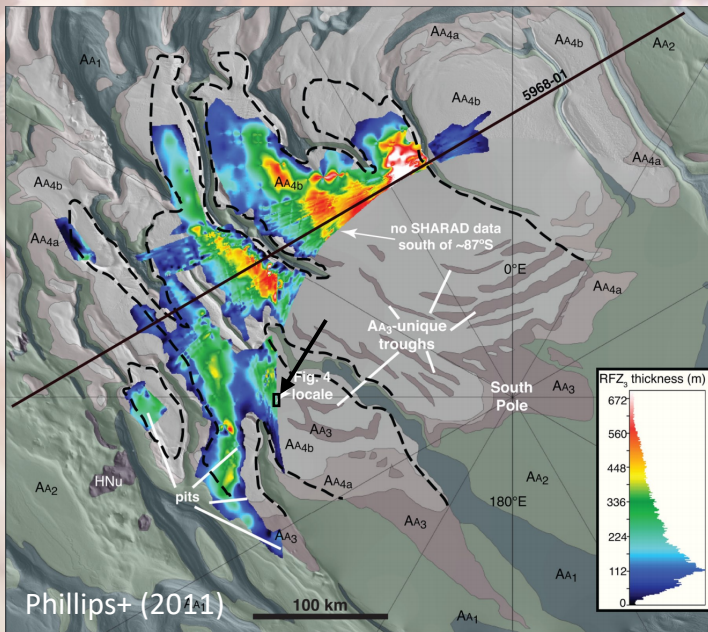
- If the massive CO<sub>2</sub> deposit is sequestered from the atmosphere, the same problem of “extraordinary accident” exists.
- “The [RSPC CO<sub>2</sub>] reservoir is small and cannot function as a long-term buffer to the more massive atmosphere.” –Byrne and Ingersoll (2003)
- How did the (dark) H<sub>2</sub>O layer become emplaced?

*“Solid CO<sub>2</sub> can not survive burial beneath any low-albedo [material] “dirt,” even temporarily, since the subsurface temperature exceeds the sublimation point of the solid and CO<sub>2</sub> will escape as a gas.*

*In addition, any burial process ... will necessarily be slow, with individual particles warming the CO<sub>2</sub> around them, and sinking from solar view by subliming CO<sub>2</sub> into the atmosphere.*

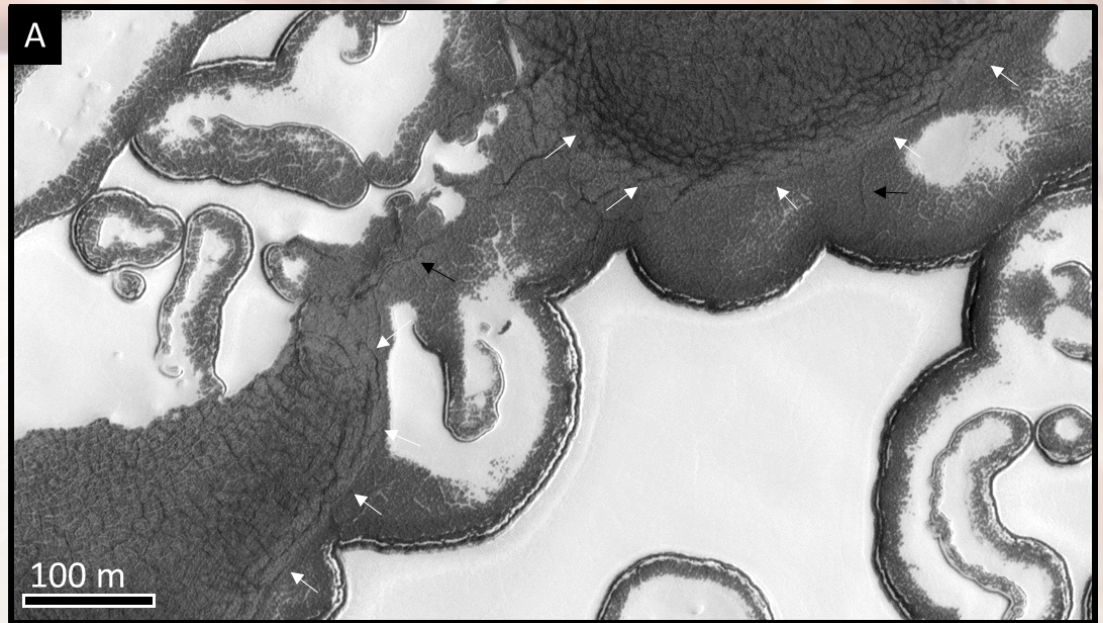
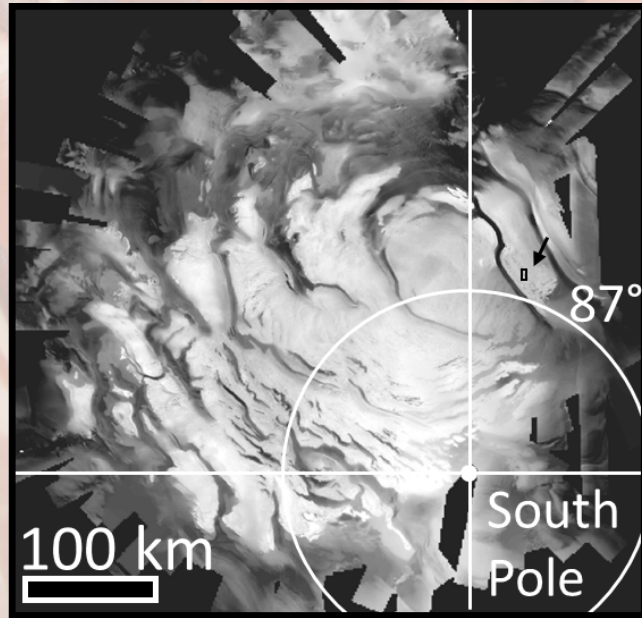
*Thus, a scum layer of dark (low albedo) material may be buried beneath a topmost layer of frost, but as soon as this topmost layer is removed, the dark dust [or H<sub>2</sub>O ice] will heat up and any CO<sub>2</sub> beneath it will escape.” –Murray and Malin (1973)*

# Does the H<sub>2</sub>O seal the deposit?

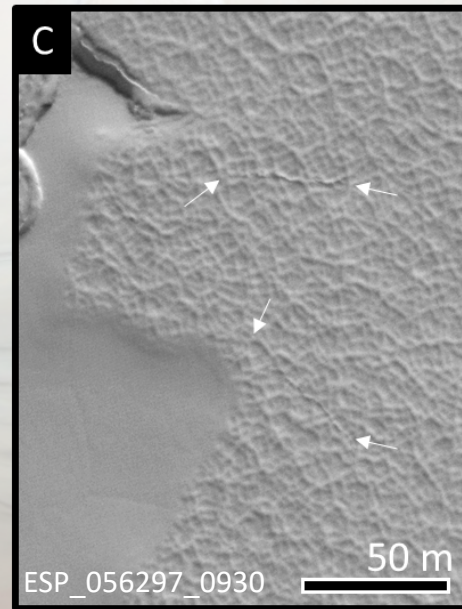
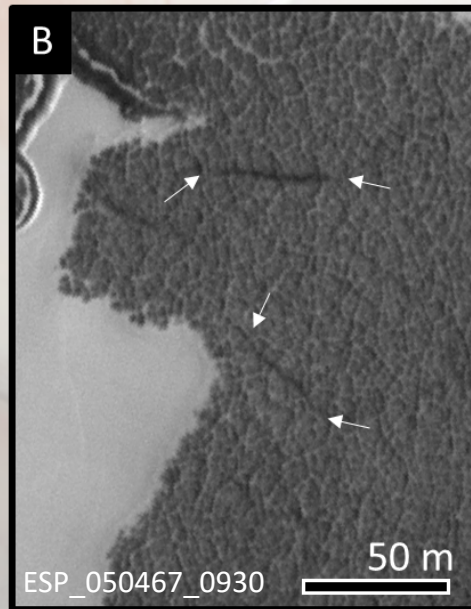


- “All of these smaller troughs, depressions, and pits appear to result from erosion and removal of unit A<sub>A3</sub> [the massive CO<sub>2</sub> deposit], with a strong component of sublimation and collapse.”
- “The fracturing, not found in other SPLD units, may be a response to continuing unit A<sub>A3</sub> sublimation after the pits had first formed.”

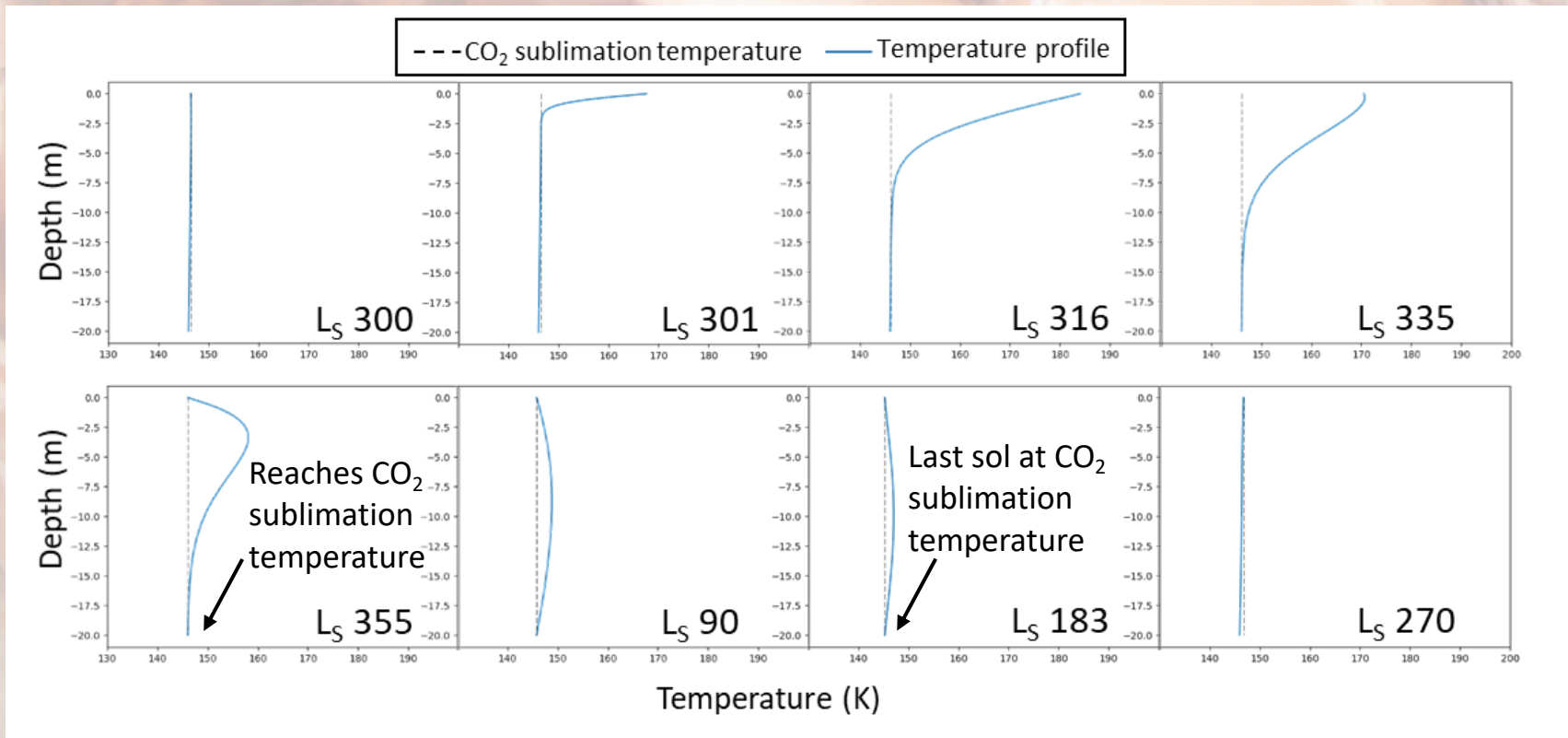
# Does the H<sub>2</sub>O seal the deposit?



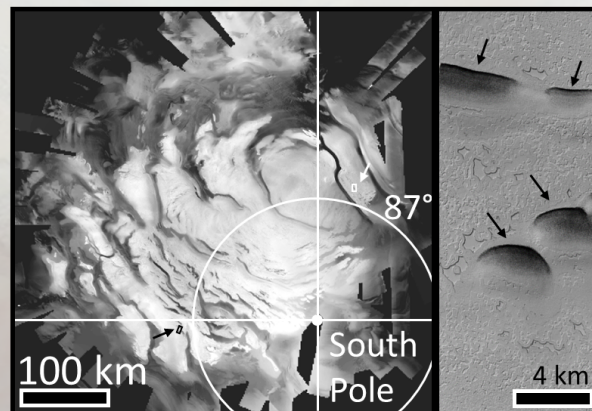
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# H<sub>2</sub>O layer not an effective thermal insulator

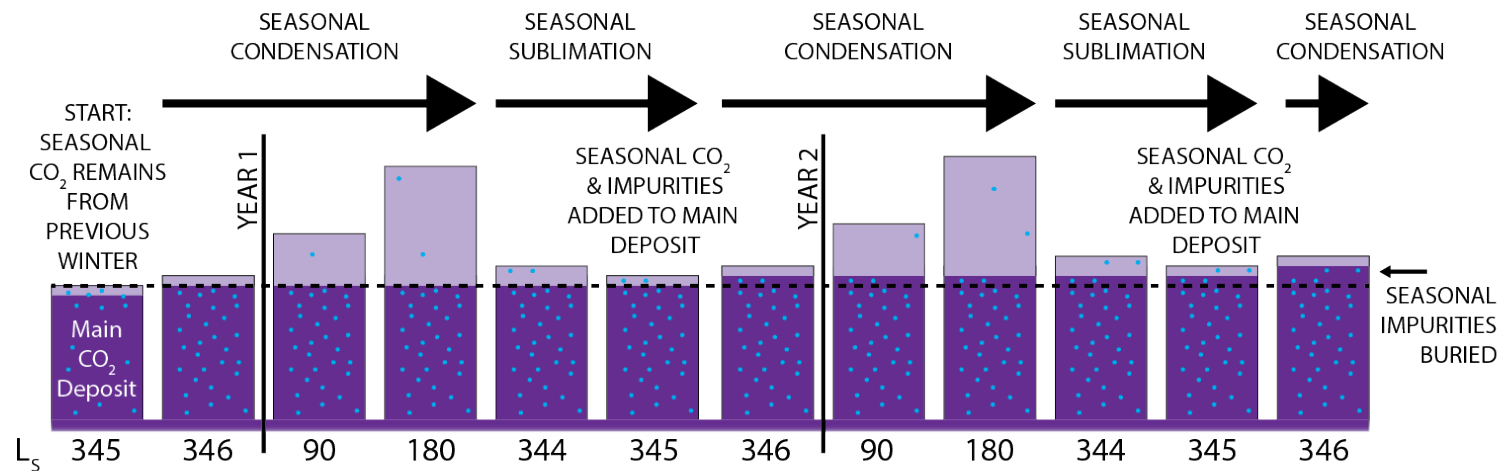


Modern-day model run,  
condensed CO<sub>2</sub> forced  
to zero at L<sub>S</sub> 300



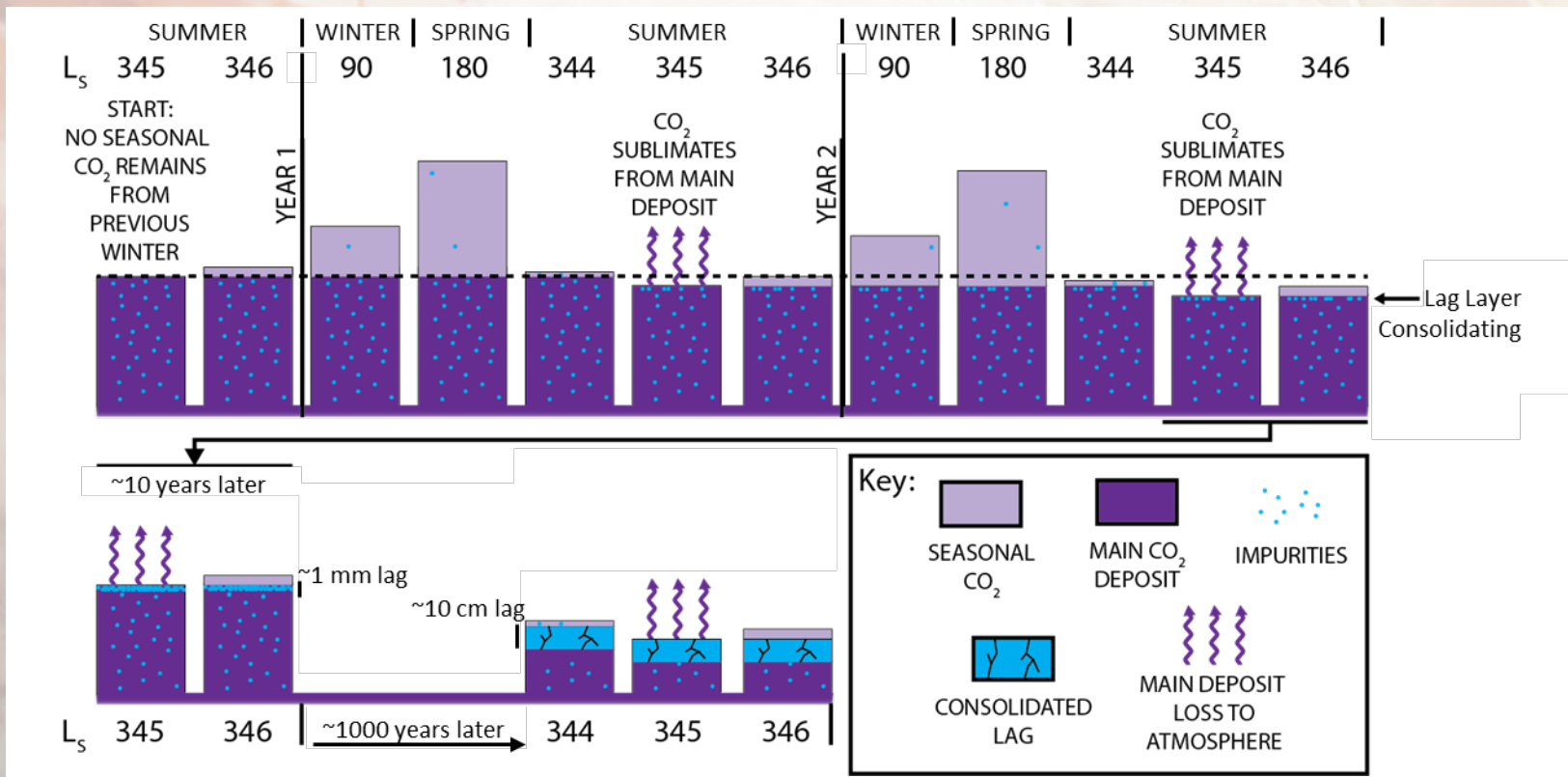
Regions of dark H<sub>2</sub>O layer  
are exposed by L<sub>S</sub> 297

ESP\_013775\_0931

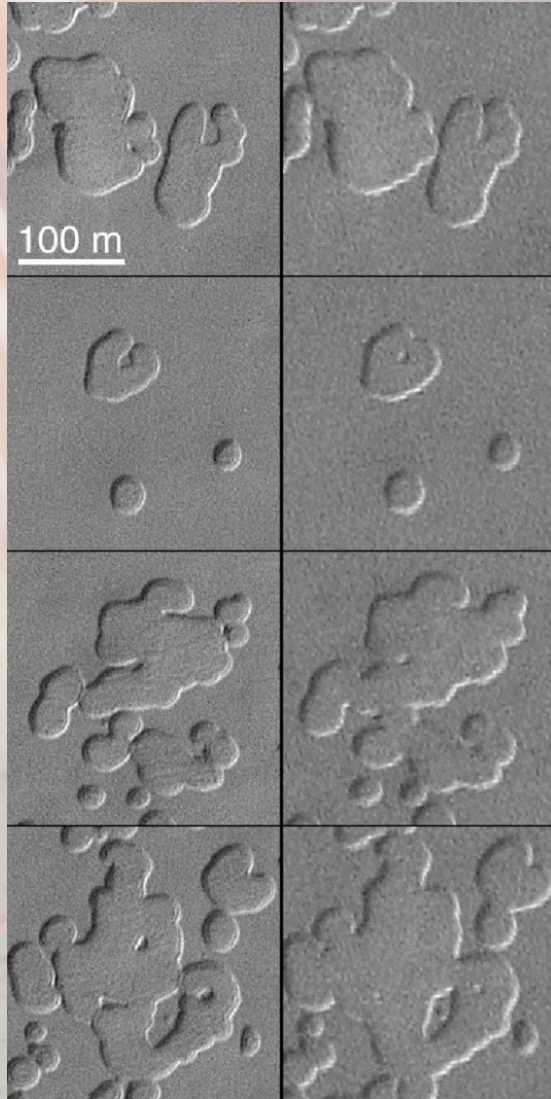


# Why the RSPC exists

- “A scum layer of dark (low albedo) material may be buried beneath a topmost layer of frost, but as soon as this topmost layer is removed, the dark dust [or  $H_2O$  ice] will heat up and any  $CO_2$  beneath it will escape.” –Murray and Malin (1973)
- But what happens next?



# The pits are a complication



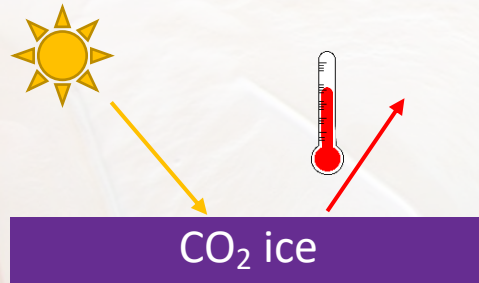
- Uneven CO<sub>2</sub> deposition permits some RSPC regions to maintain perennial CO<sub>2</sub> cover while other regions expose bare lag at the end of summer.
- Horizontal erosion redistributes the entire RSPC to transiently expose all areas of the underlying lag on 10<sup>2</sup> yr timescales ( $\ll 10^5$  yr orbital timescales).

# Mars' Pressure History

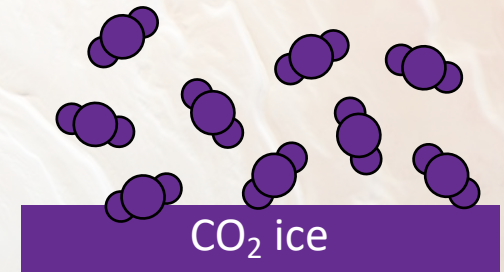
Use a look-up table:



Any orbit

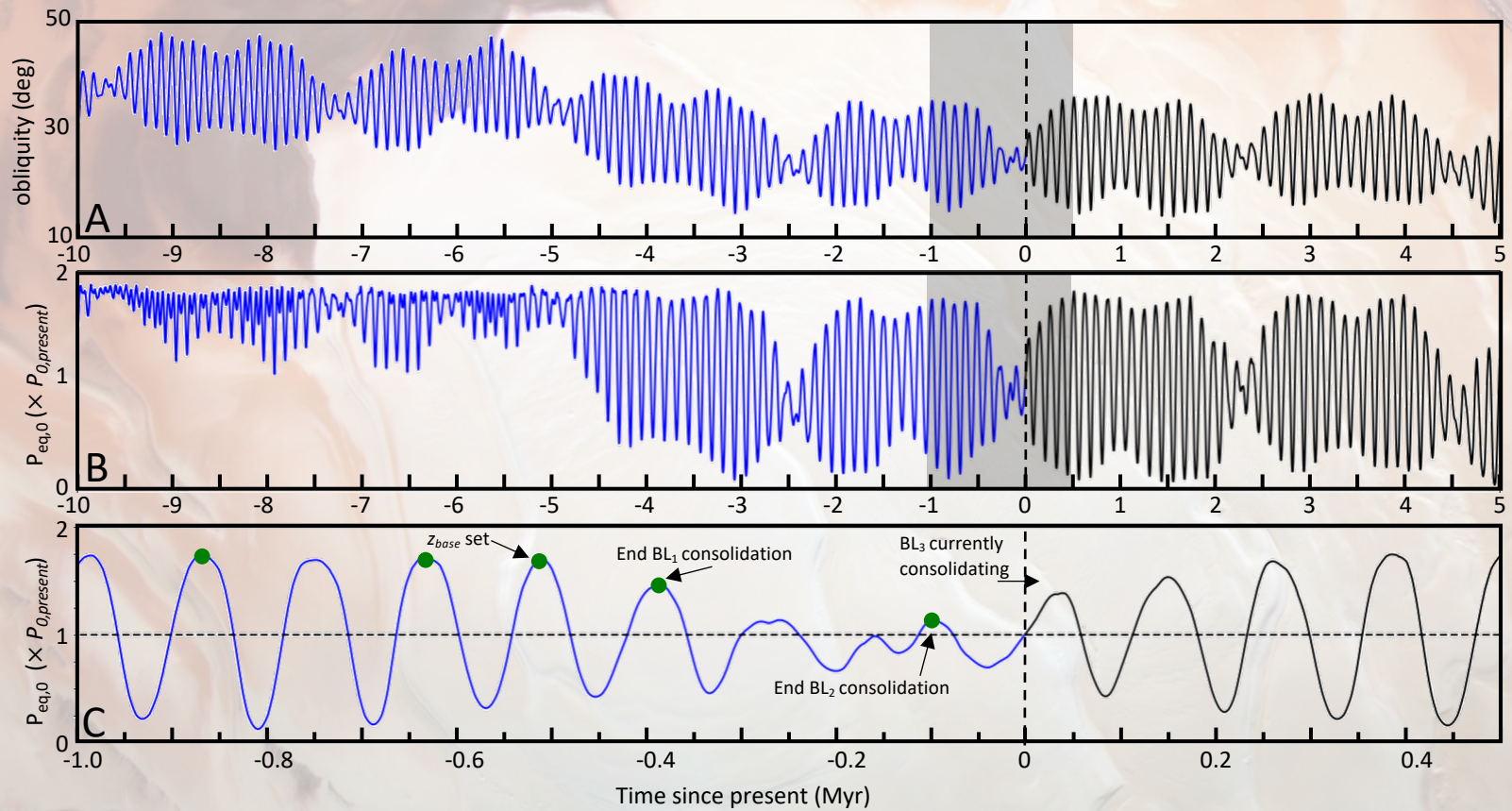


Equilibrium Frost  
Temperature

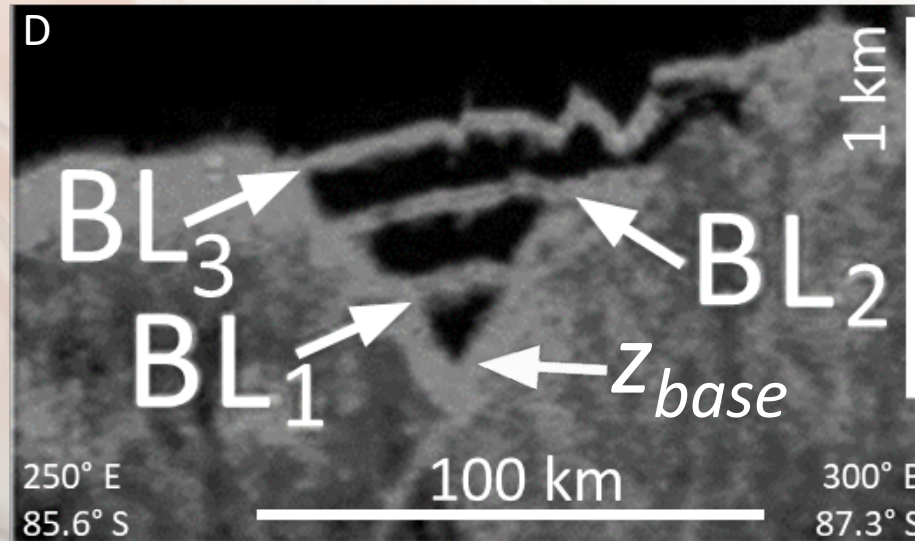
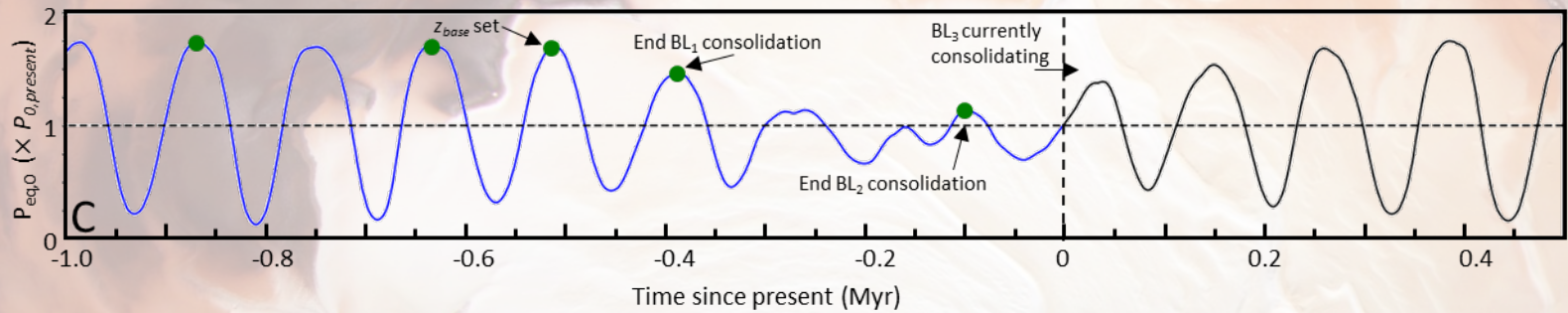


Equilibrium  
Pressure

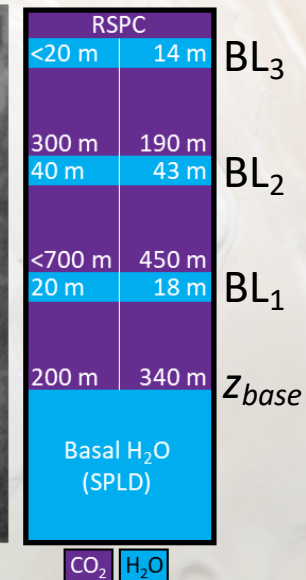
# Mars' Pressure History



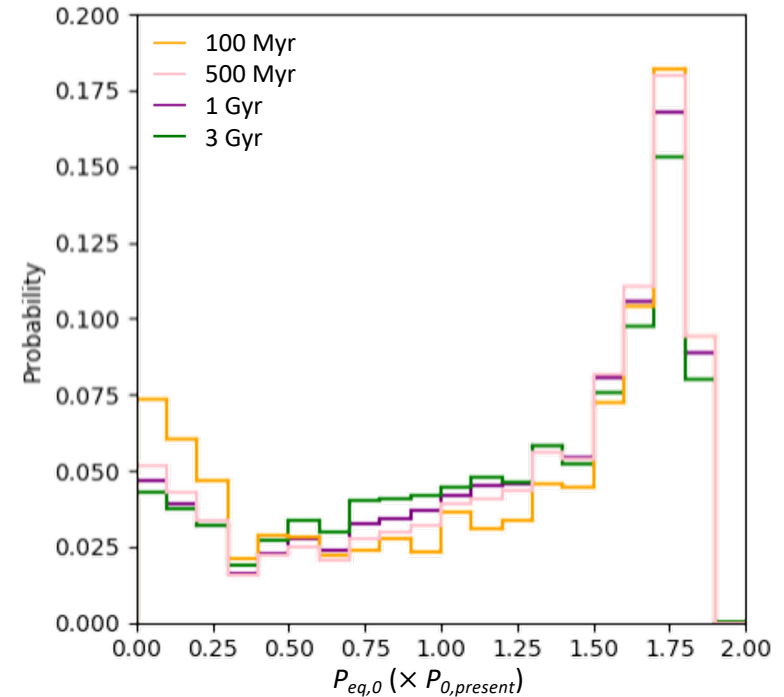
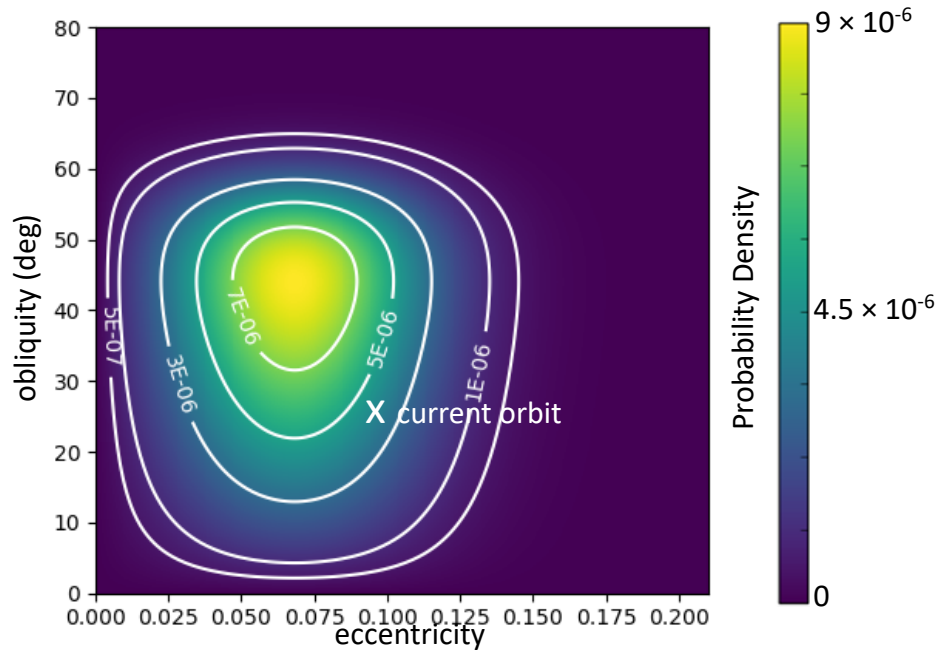
# Stratigraphy of the massive CO<sub>2</sub> deposit



**E. Stratigraphy**  
Obs. Model



# Long-term pressure history of Mars



- Median Amazonian pressure:  $1.32 \times$  present
- Interquartile range: 0.77 to  $1.67 \times$  present

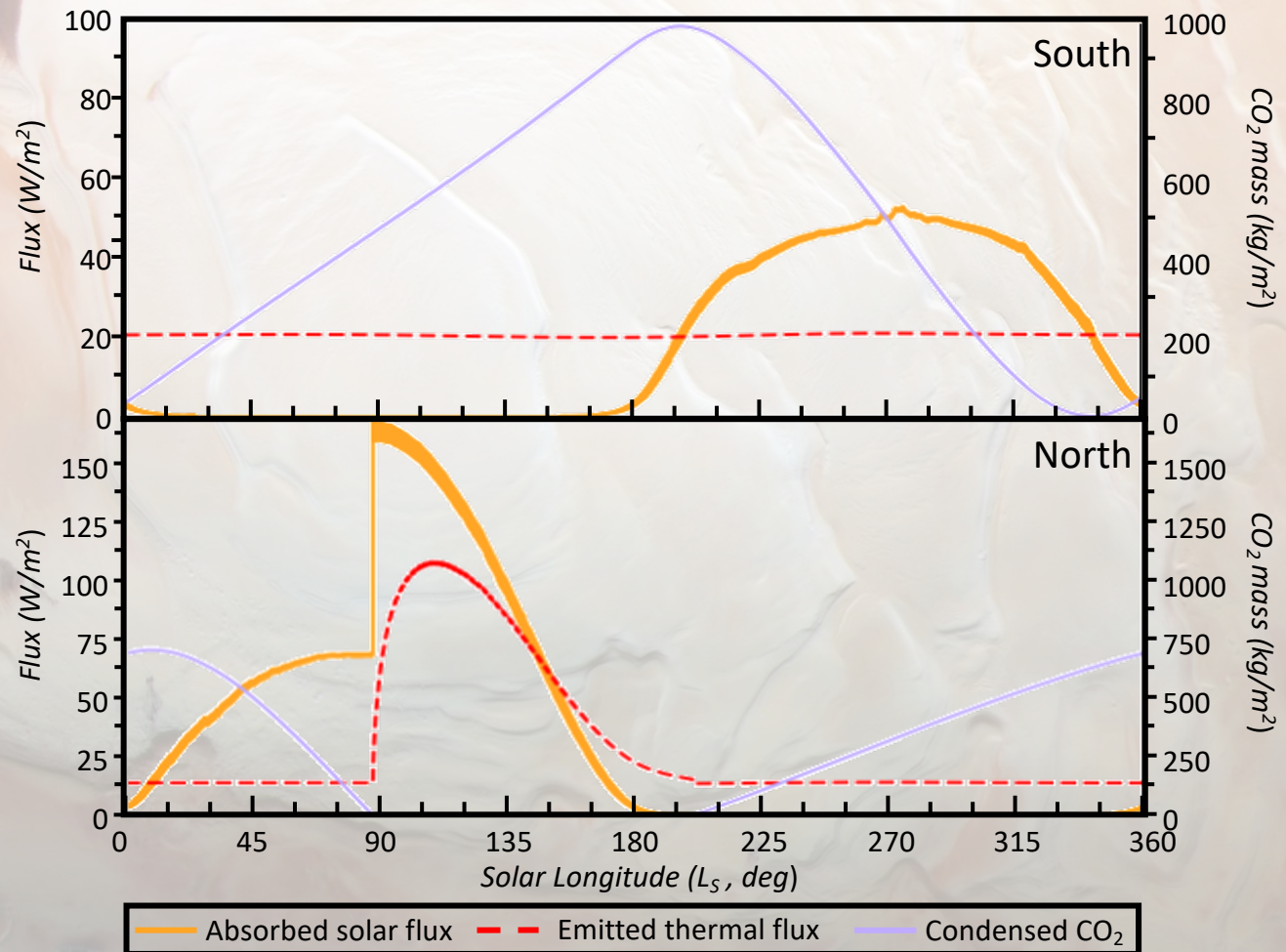
# Why is the permanent CO<sub>2</sub> in the south?

*"There is no reason to suppose a permanent CO<sub>2</sub> southern cap would be at a systematically lower temperature than the northern one."*

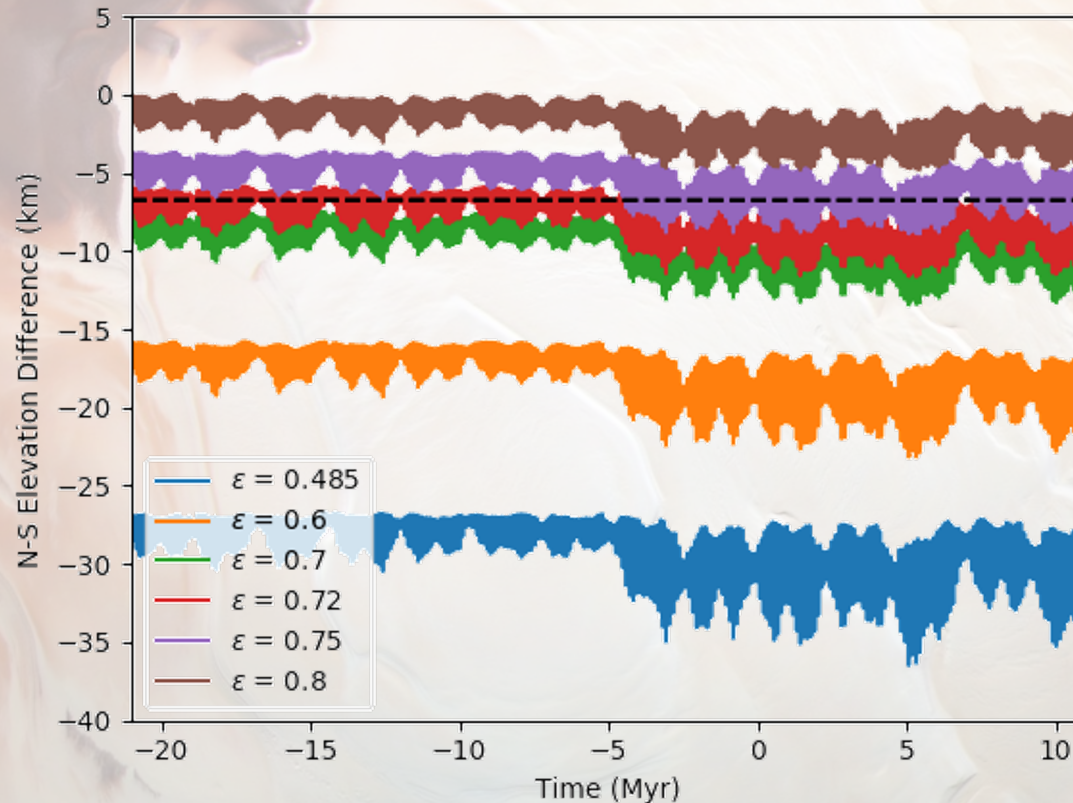
– Murray and Malin (1973)

$$\bar{A}_{CO_2} \approx 0.7$$
$$\epsilon_{CO_2} \approx 0.8$$

$$\bar{A}_{CO_2} \approx 0.63$$
$$\epsilon_{CO_2} \approx 0.49$$

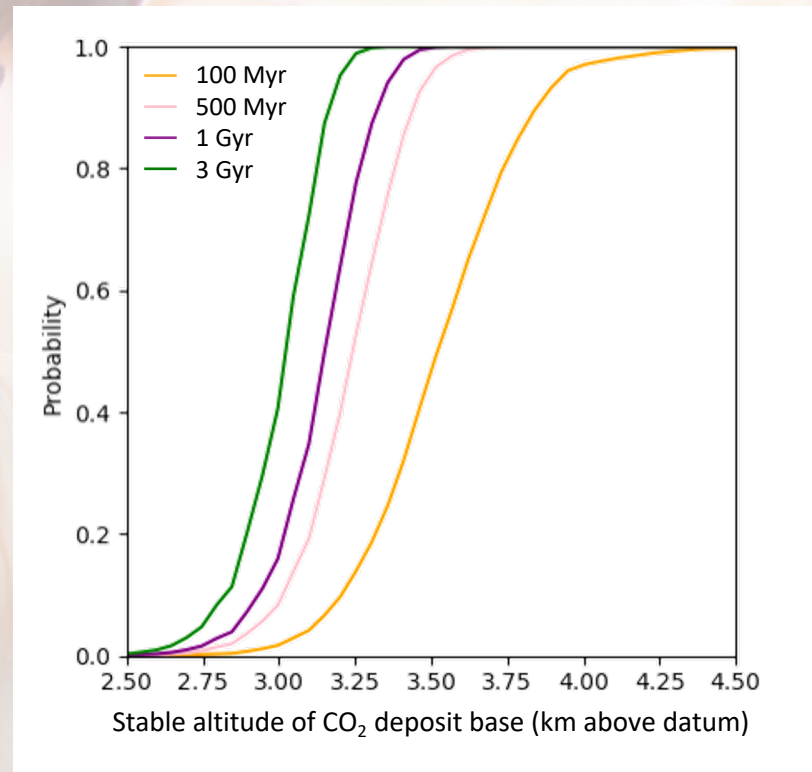


# Will perennial northern CO<sub>2</sub> ever exist?



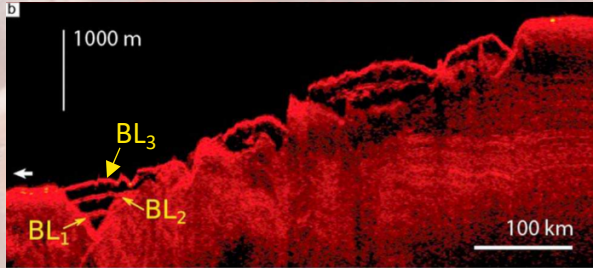
Would require significant changes to  $\bar{A}_{CO_2}$  and/or  $\epsilon_{CO_2}$

# CO<sub>2</sub> protects the SPLD at high obliquity



- CO<sub>2</sub> protects the SPLD from ablating.
- CO<sub>2</sub> does not protect the NPLD.

# Conclusions 1

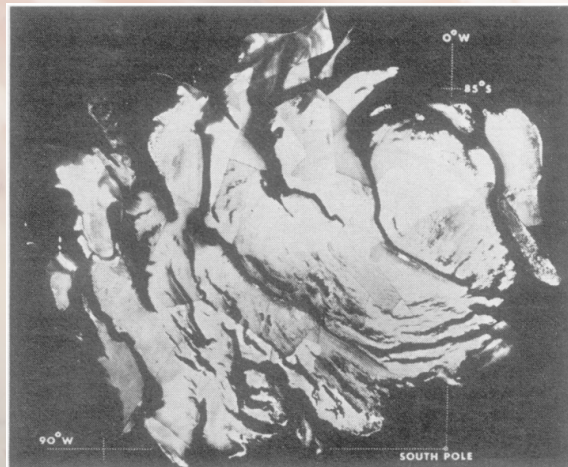
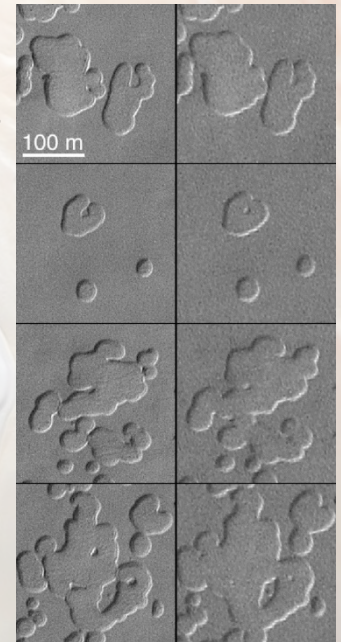


1. How was the massive CO<sub>2</sub> deposit emplaced with its observed stratigraphy?

**Equilibrated co-evolution with the atmosphere, driven by orbital forcing. H<sub>2</sub>O impurities accumulate into lag deposits.**

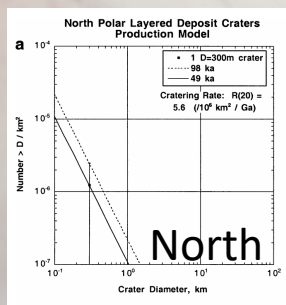
2. Why does the RSPC exist?

**Negative feedback between surface CO<sub>2</sub> ablation, dark lag formation, and basal CO<sub>2</sub> sublimation.**



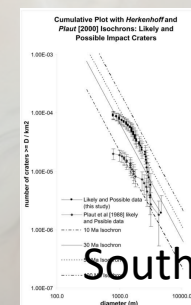
3. Why is permanent CO<sub>2</sub> at the south pole (not the north)?

**The albedo/emissivity of the southern CO<sub>2</sub> is higher, overwhelming the lower elevation of the northern cap.**



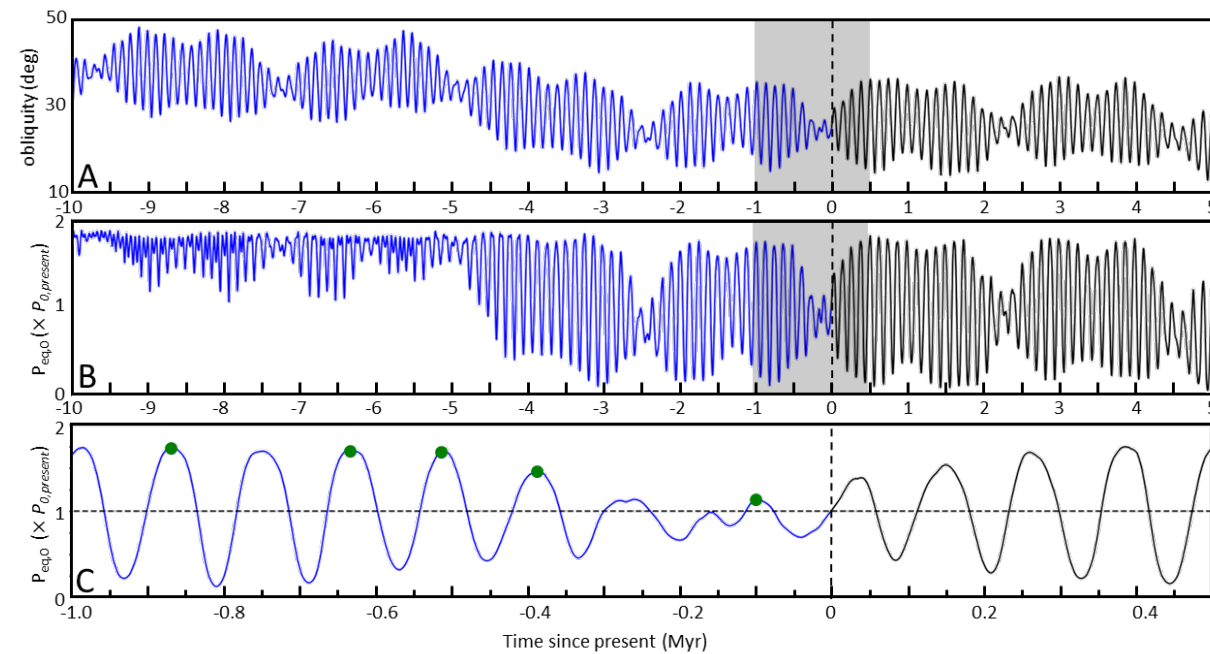
4. Why is the SPLD so old (compared to the NPLD and model predictions)?

**Perennial CO<sub>2</sub> cover protects the SPLD, but not the NPLD, from ablation at high obliquity.**

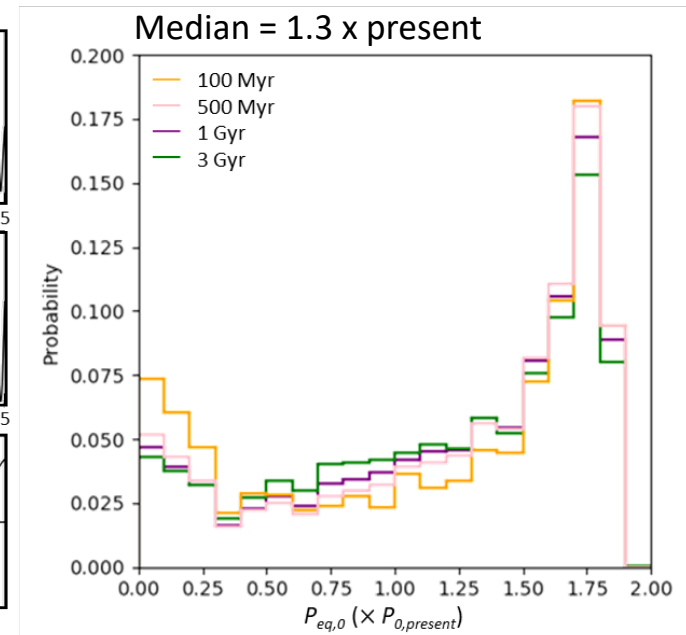


# Conclusions 2

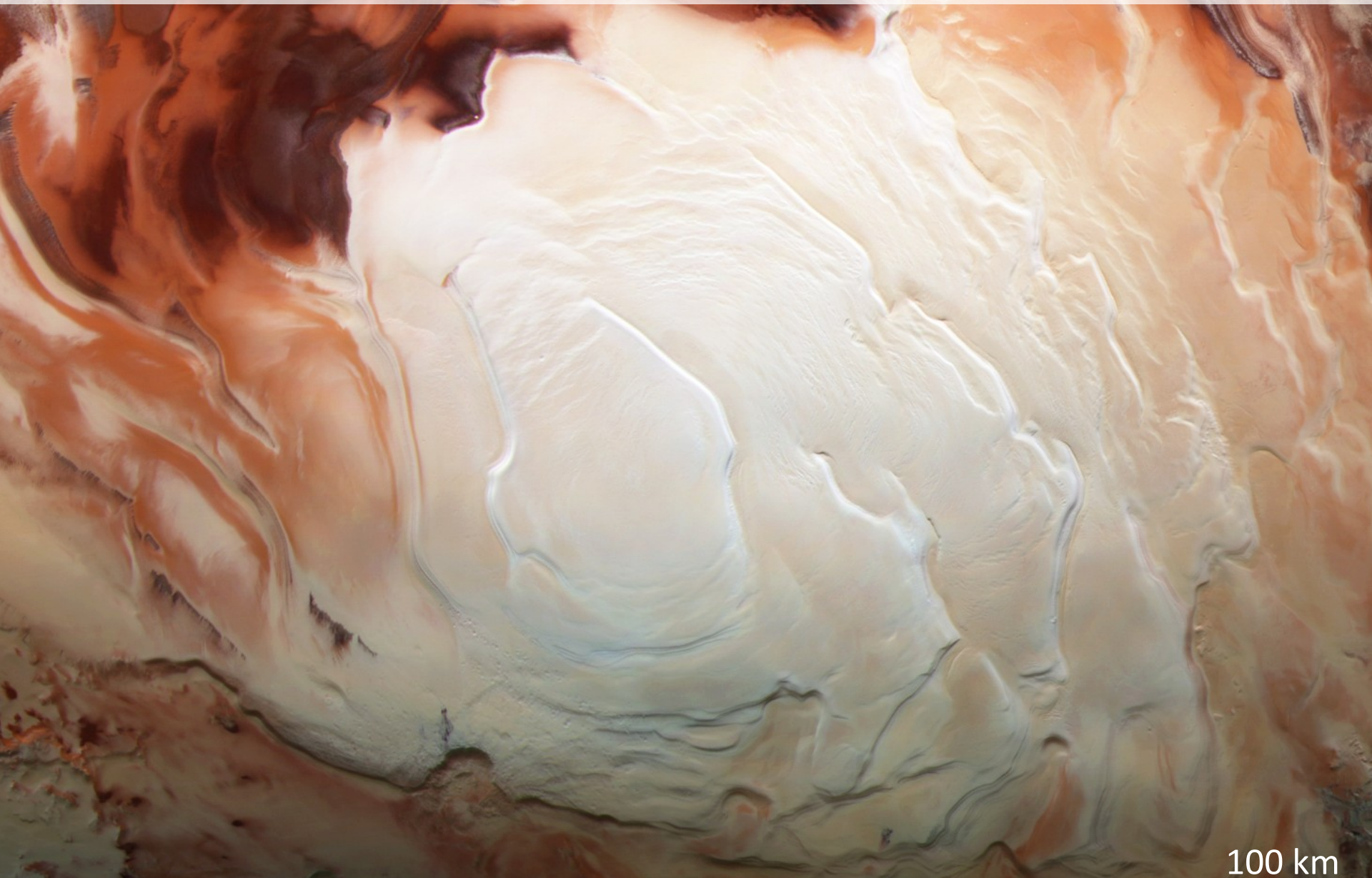
## Recent Pressure History



## Long-term Pressure History



# Questions?



100 km